Flood Plain Management Services

Coastal Storm Evaluation Halloween Storm of 1991

January 1994

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This study has been conducted under the Corps of Engineers' Flood Plain Management Services (FPMS) Program. The purpose of this study is to document and describe the impact of the Halloween Storm of October 28 to November 2, 1991 on various coastal processes and issues including: tides; winds; storm damage and erosion; and wave and water level heights. This report also describes the development and track of the storm, and provides a general overview of its impacts along the New England coast from Nantucket, Massachusetts to Portland, Maine.

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COASTAL STORM EVALUATION

HALLOWEEN STORM OF 1991

January 1994

Department of the Army
New England Division
Corps of Engineers
Waltham, Massachusetts

EXECUTIVE SUMMARY

In late October and early November of 1991, the eastern coastline of New England experienced severe flooding and erosion from an unusual coastal storm event. The storm, referred to as the Halloween Storm of 1991, was a devastating extratropical event which originally developed east of Nova Scotia, Canada and strengthened as it unexpectedly moved westward. The storm was extremely intense, causing flooding, erosion and damage along most of the east facing New England shoreline, including the coastlines of Maine, New Hampshire, and Massachusetts. According to the National Weather Service, the storm's effects were observed from along the Canadian shoreline south to the Atlantic facing shorelines of the Greater Antilles. The storm produced damages and erosion within New England comparable to the Blizzard of 1978.

This study has been conducted under the Corps of Engineers' Flood Plain Management Services (FPMS) program. The FPMS program is authorized under Section 206 of the Flood Control Act of 1960 (PL 86-645) and authorizes the Corps of Engineers to provide planning and technical assistance to states in matters relating to flooding and flood plain management.

The purpose of this study is to document and describe the impact of the Halloween Storm of October 28 to November 2, 1991 on various coastal processes and issues including: tides; winds; storm damage and erosion; and wave and water level heights. This report also describes the development and track of the storm, and provides a general overview of its impacts along the New England coast from Nantucket, Massachusetts to Portland, Maine. A comparison of the severity of the Halloween Storm to the Blizzard of 1978 was also accomplished. Various wave and water level parameters from both storms were compared on a regional scale to aid in determining what may have been the contributing factor or factors to the severity of the Halloween Storm.

The Halloween Storm of 1991 was a unique extratropical event resulting from three significant meteorological systems: (1) a subtropical low which quickly developed into Hurricane Grace located southwest of Bermuda; (2) an intense near record high pressure system over northern Quebec which was moving southeastward over the North Atlantic and across Nova Scotia and New England; and, (3) a low pressure area which developed along the cold front associated with the high pressure over Quebec and which eventually intensified southeast of the Canadian Maritimes. This third system is what eventually became the Halloween Storm of 1991.

The combination of these three systems; the hurricane, the high pressure along the East Coast, and the strengthening low pressure area, produced a nearly 1200 nautical mile fetch of gale and storm force winds (32 to 72 miles per hour) from Newfoundland, Canada to Florida.

Two computer models were used to develop wave and water level hindcasts for the Blizzard of 1978 and the Halloween Storm of 1991. Numerical modeling is applied as an interpolation tool to provide information in space and time where it is lacking. The first was Wave Information Studies (WIS) Wave Model (WISWAVE), Version 2.0. This model was used to develop wave characteristics for these two storms along the east facing New England shoreline. The water level hindcast used SURGE II to simulate the non-flooding water level due to wind induced surge at the coast. The results of the hindcast and a discussion of the modeling procedure are contained in Appendix D - Wave and Water Level Hindcast which contains the report "Wind Wave and Water Level Hindcast Results for the Blizzard of 1978 and the Halloween Storm of 1991 for Coastal New England, Final Report - June 1993". The model output has been exhibited at thirteen specific locations selected from the seventy-three nearshore stations where information was generated. Further information at these other sites may be obtained by contacting the U.S. Army Corps of Engineers, New England Division. Table 11 within the report is a listing of the thirteen stations and their locations.

Throughout the course of this study meetings were held with various state agencies from Maine, Massachusetts, and New Hampshire. The question of return period was repeatedly raised. However, a particular frequency can not be associated with either storm. Frequencies or return periods are better associated with only certain aspects of a storm event, such as maximum stillwater level, storm surge, or wave height at a particular location. Frequency, or return period, of an event depends on the specific parameters which may be of particular importance to the reader.

This study attempts to provide a greater understanding of the spatial and temporal wave and water level conditions for the two storms. It can be used as a planning tool for more site specific analysis of extreme storm conditions. The information generated during this study, in particular the wave and water level hindcasting, is designed to be used as the framework for more detailed site-specific planning and engineering investigations and studies. It can be utilized to better understand the wave and water level conditions at a specific site associated with extratropical events through the application of other engineering methods to resolve conditions at a specific onshore site. Since real-time nearshore wave characteristics are not available on a large scale, a wave and water level hindcast method was used to generate storm conditions at five nautical mile intervals along the shoreline from Nantucket, Massachusetts north to Portland, Maine. There are 73 stations at which hindcast wave and water level information is available for the Blizzard of 1978 and the Halloween Storm, and thirteen of these stations have been presented in this report. Information for the other stations can be obtained through the Corps of Engineers, New England Division.

The major findings of this report are as follows:

- The storm surge elevations of the Halloween Storm are equivalent to return periods of approximately 90 years and 10 years at Boston and Portland, respectively. This is in contrast to return periods of 35 years and 4 years at Boston and Portland,

respectively for the Blizzard of 1978. At Boston, the surge was the greatest of modern record for the Halloween Storm.

- The Halloween Storm coincided with a period of normal astronomic tides, occurring one week after spring tides caused by a full moon. In contrast, the Blizzard of 1978 coincided with a period when the astronomic tidal cycle was influenced by a perigean spring tide occurring during the peak of a nodal tide. The nodal tide occurs once every 18.6 years and coincidentally peaked in early February, 1978 at the time the Blizzard occurred.

- The frequency of ocean stillwater level for the Halloween Storm is probably not a true indicator of the storm's overall severity. This is because the observed damages were comparable to that which resulted from the Blizzard of 1978 even though the stillwater level return periods (at Boston) were 17-years for the Halloween Storm and 100-years for the Blizzard of 1978. This is an indication that extreme wave action was a primary factor contributing to the Halloween Storm's severity.

- The winds for the Blizzard of 1978 and the Halloween Storm were similar at Portland, Maine, but at Boston, Massachusetts the 1991 winds did not reach levels recorded in 1978. In addition, coastal meteorological stations recorded barometric pressures during the Halloween Storm which were quite high for this type of storm. However, the differences in pressure between the center of the Halloween Storm and the coast produced large pressure gradients and their associated high winds.

- Reported erosion throughout the study area ranged from a few feet to 30' (9.1 m). It appears the greatest erosion occurred along the east facing shorelines of Cape Cod and Nantucket. Storm damage has been documented and is contained in Appendix E. This includes a descriptive account of the damages and erosion throughout the study area.

- An economic assessment was conducted summarizing insurance claims, payments and other disbursements. The total monetary amount paid on flood insurance claims and funds disbursed to municipalities within the study area was greater for the Halloween Storm ($93,788,200) than for the Blizzard of 1978 ($63,434,900). These funds are expressed in 1991 dollars and are directly comparable.

- Hindcast peak wave periods were more variable throughout the study area during the development and peak of the Halloween Storm than at any time during the Blizzard of 1978. Observed peak periods in some cases exceeded 20 seconds during the Halloween Storm. However, when compared with the hindcast peak wave periods for the Halloween Storm, the observed peak periods were actually 4 to 6 seconds greater. This discrepency is due to the model's limitations in identifying differences between wave periods generated by local seas and those generated by swell wave

conditions. Therefore, it is recommended that sound engineering judgement be used when applying the hindcast wave period data for further evaluation of site specific conditions.

- Hindcast peak wave heights during the Blizzard of 1978 were relatively uniform throughout the study area. Peak wave heights for the Halloween Storm were more varied throughout the study area and were considerably larger off Cape Cod and Nantucket. The wave heights and their duration in the southern portion of the study area were a significant factor contributing to the damages and erosion resulting from the Halloween Storm. For the Blizzard, wave heights were higher in the northern part of the study area, such as in Maine.

- A storm power classification system developed for extratropical storms was used to compare the intensities of the Blizzard of 1978 and Halloween Storm. The Blizzard exhibited greater storm power in New Hampshire and Maine due mostly to wave heights being larger than those experienced during the Halloween Storm. However, over the southern portion of the study area (Cape Cod, Nantucket), wave heights were larger and their duration about 30 hours longer for the Halloween Storm than for the Blizzard of 1978. This resulted in the Halloween Storm being up to three times more powerful in the Cape Cod and Nantucket areas. This is a primary reason for the extensive damage and erosion observed in these areas as a result of the Halloween Storm.

- Due to the similarity in hindcast wave direction for both storm events, it is doubtful that this parameter contributed to major differences exhibited in onshore damages. However, local variations in wave direction were not examined and may have contributed to localized differences in damages between the two storms.

- In general, hindcast water levels were about 2' (0.6 m) higher during the Blizzard than during the Halloween Storm. However, the duration of high water levels (arbitrarily defined as when the storm surge is greater than 1' (0.3 m)) was 90 hours for the Halloween Storm and 45 hours for the Blizzard at Boston. Therefore, it appears that the New England coast was subjected to higher than normal water levels for a longer period of time during the Halloween Storm than during the Blizzard of 1978.

- The Halloween Storm track provided the opportunity for a longer duration of larger waves and higher than normal water levels to impact the New England coast.

- There has been concern that the existing 100-year flood boundaries identified in flood insurance studies accomplished by FEMA may not adequately address the flooding potential from events such as the Halloween Storm. The hindcast wave

characteristics for the Halloween Storm frequently exceeded the wave parameters used to develop the 100-year wave envelope in various flood insurance studies. In some cases, hindcast wave heights exceeded the significant wave height used by the flood insurance study. Also, the hindcast wave periods for the Halloween Storm, when adjusted to match observed wave periods, exceeded by 5 to 8 seconds those periods used in the flood insurance studies. However, FEMA believes that revisions to the delineation of flood boundaries are not warranted and that the 100-year flood boundaries and wave envelopes defined in the flood insurance studies are adequate representations of typical 100-year water level and wave characteristics.

- A comparison of the Halloween Storm's hindcast water levels with stillwater elevations obtained from the flood insurance studies reveals that the hindcast water levels are consistently near or greater than the 100-year stillwater levels. However, the hindcast water levels are for points some distance offshore. Without further nearshore refinement, the water level hindcast results are inconclusive for comparing to the 100-year flood boundary developed within the flood insurance studies.

The conclusions of this study are:

- 1) the frequency of a storm is important for characterizing the severity of the event and comparing it with other storms. However, the wave climate is not normally reflected in the return period, therefore, the frequency can be misleading and should not be misinterpreted;

- 2) the wave climate hindcast information can be used as the framework for further site-specific analysis of the impacts of northeasters within New England. However, hindcast water levels are inconclusive for developing return periods from or for comparing to the 100-year flood boundaries established by flood insurance studies, and hindcast wave parameters for the Halloween Storm frequently exceeded those used within the flood insurance studies;

- 3) further detailed monitoring of offshore sea conditions is required to adequately model and assess the impacts of northeasters; and,

- 4) there is no classification system for extratropical storms (northeasters) similar to the Saffir-Simpson Hurricane Intensity Scale. A similar scale for extratropical storms could aid in determining the potential risks of an approaching storm.

Based on the conclusions above, it is recommended that:

- 1) the frequency of an event be carefully identified and fully explained before this information is released to other agencies, emergency management personnel, the media and the general public;

- 2) site-specific studies be identified and initiated to identify specific causes of coastal related damages and that further refinement of nearshore wave parameters should be accomplished;

- 3) a similar evaluation be accomplished for comparing and contrasting the wave and water level climate and economic losses and damages between the Halloween Storm and a more recent storm event such as the December 1992 northeaster. This would provide more reliable data, particularly wave and water level observations, damages, and insurance claim and reimbursement information;

- 4) obtaining reliable nearshore sea state conditions through wave gage monitoring and beach/shoreline surveys be pursued to verify existing wave hindcasting methods and serve planning and design purposes within New England Division; and,

- 5) a classification system for extratropical storms similar to the Saffir-Simpson Hurricane Intensity Scale be developed to aid emergency management agencies and personnel in alerting the public to anticipate certain risks and results from a particular type of storm.

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I. INTRODUCTION

Study Background

In late October and early November of 1991, the eastern coastline of New England experienced severe flooding and erosion from an unusual coastal storm event. The storm, referred to as the Halloween Storm of 1991, was a devastating extratropical event which originally developed east of Nova Scotia, Canada and strengthened as it unexpectedly moved westward. The storm was extremely intense, causing flooding, erosion and damage along most of the east facing New England shoreline, including the coastlines of Maine, New Hampshire, and Massachusetts. According to the National Weather Service, the storm's effects were observed from along the Canadian shoreline south to the Atlantic facing shorelines of the Greater Antilles. The storm produced damages and erosion within New England comparable to the storm of record, the Blizzard of 1978 (February 6-8).

The severity of the storm's impact was a result of the unusual waves that were observed during the storm's westerly track toward the New England coast. Deep water wave data indicated that wave periods in excess of 20 seconds were observed as compared to the 12 to 14 second wave periods typically associated with northeaster storms in the New England region. Deepwater wave heights in excess of 40 feet (12 meters) were also observed.

Coastal Zone Management and responsible flood damage mitigation agencies within the three states are concerned that the existing 100-year flood boundaries used for regulatory purposes may not adequately address the flooding potential from storms like the October 1991 event. To assist in addressing this concern, the states would like a better understanding of the storm and its likelihood of future occurrence; a comparison of the damage areas effected from this storm with past severe coastal storms; and an evaluation of the factors which influenced the location of damage centers.

Study Authority

This study has been conducted under the Corps of Engineers' Flood Plain Management Services (FPMS) program. The FPMS program is authorized under Section 206 of the Flood Control Act of 1960 (PL 86-645). This program authorizes the Corps to provide planning and technical assistance to states, regional authorities, and communities in matters relating to flooding and flood plain management.

Study Purpose

The purpose of this study is to document and describe the impact of the Halloween Storm of October 28 to November 2, 1991 on various coastal

processes and issues including: tides; winds; storm damage and erosion; and the correlation of damage and erosion with wave and water level heights. This report also describes the development and track of the storm, and provides a general overview of its impacts along the New England coast from Nantucket, Massachusetts to Portland, Maine.

A comparison of the severity of the Halloween Storm to the Blizzard of 1978 was also accomplished. Various wave and water level parameters from both storms were compared on a regional scale to aid in determining what may have been the contributing factor(s) to the severity of the Halloween Storm.

It is anticipated that this study will be used by Maine, New Hampshire, and Massachusetts as a planning tool for identifying areas of particular concern which may need further study and also as a reference for possibly predicting generalized impacts (damages and erosion) of future storm events. This effort is meant to lay the groundwork for further, more detailed site investigations.

II. HALLOWEEN STORM OF 1991 DEVELOPMENT & HISTORY

Introduction

The Halloween Storm of 1991 was a unique extratropical event resulting from three significant meteorological systems: (1) a subtropical low which quickly developed into Hurricane Grace located southwest of Bermuda; (2) an intense near record high pressure system (1046 millibars) over northern Quebec which was moving southeastward over the North Atlantic and across Nova Scotia and New England; and, (3) a low pressure area which developed along the cold front associated with the high pressure over Quebec and which eventually intensified southeast of the Canadian Maritimes. This third system is what eventually became the Halloween Storm of 1991.

The development of the low pressure cell southeast of the Canadian Maritimes coincided with Hurricane Grace reaching its maximum strength. Due to the circulation of the hurricane to its south, the low pressure area stalled and subsequently strengthened. Fed by the cold, dry arctic air from the high pressure system over northern Quebec, and the warm, moist subtropical air from Hurricane Grace, the low became extremely intense having a central pressure of 972 millibars. The leading edge cold front of the high pressure area over Quebec originally prevented Hurricane Grace from moving toward the coast. As the low pressure area moved northeast along this cold front, it stalled and strengthened due to the presence of Hurricane Grace. The cold front pushed through Grace and the intensifying low southeast of the Canadian Maritimes eventually absorbed the remnants of the hurricane. At the same time, the high pressure area originally located over Quebec had begun to weaken, allowing the extratropical storm to drift westward toward the East Coast of the United States.

The combination of these three systems; the hurricane, the high pressure area (anticyclone) along the East Coast, and the strengthening low pressure area (cyclone), produced a nearly 1200 nautical mile fetch of gale and storm force winds (32 to 72 miles per hour) from Newfoundland, Canada to Florida.

Antecedent Conditions

The antecedent conditions in Boston for the Halloween Storm, as recorded at Logan International Airport, included seven days of measurable precipitation for the month of October. This included only two significant rain events for which precipitation measured less than an inch for each. The first occurred October 6 with precipitation measuring 0.88 inches and the other occurred October 18, with precipitation measuring 0.84 inches. There was no measurable precipitation between the October 18 rainstorm and the beginning of the Halloween Storm on October 30. The greatest 24-hour precipitation for the month of October occurred from the 30th to the 31st and measured 1.56 inches. This information was derived from a monthly summary of local climatological data provided by the National Climatic Data Center.

Synoptic History

The Halloween Storm resulted from the interaction of numerous meteorologic events, as described above. The following is a synoptic history of the development and life of the storm. Figure 1a shows the storm tracks of the Halloween Storm, Hurricane Grace, and the Blizzard of 1978. Table 1 shows the track of the Halloween extratropical event and Figures 1b through 1g show surface analysis of the various meteorologic systems. The information for this section was compiled from various reports provided by the National Weather Service and the National Oceanic and Atmospheric Administration.

Saturday, October 26, 1991

At 0100 Eastern Standard Time (EST) (0600 Universal Time Coordinates, UTC) satellite imagery and data buoy reports suggested the strengthening of a subtropical low centered at approximately 27 degrees North, 66 degrees West. This system eventually developed into Hurricane Grace.

At about the same time, a weak wave appeared in the lower Midwest along a cold front extending northeast into Canada. This front was the leading edge of an intensifying high pressure area over northern Quebec.

Sunday, October 27, 1991

At 1100 EST (1600 UTC) the subtropical low had intensified and reached tropical storm status. Tropical Storm Grace had a slow westward movement, and by 1700 EST (2200 UTC), Grace had been upgraded to hurricane status.

The weak wave which appeared along the cold front now developed into a weak low pressure area centered over eastern Lake Ontario as the cold front of October 26 passed through New England. (See Figure 1b.) The National Weather Service (NWS) forecasted the low to move in an east-southeast direction, while the intensifying high pressure area would move from just east of Hudson Bay to the east-southeast. This would eventually result in a greatly increased pressure gradient along the East coast during the next 36 hours.

Monday, October 28, 1991

The previously weak low pressure area had strengthened and developed southeast of Nova Scotia. (See Figure 1c.) This was a result of the high pressure area now situated north of New England supplying the low with cold, dry air and Hurricane Grace, now situated west of Bermuda, contributing warm, moist subtropical air. These events led to a greatly tightened pressure gradient between the low pressure area, the hurricane, and the Canadian high. This situation resulted in a strong northeast fetch of gale force winds, especially to the north and west of the strengthening low pressure area near Nova Scotia. The low pressure area was initially located a few hundred miles east of Nova Scotia and was classified as an extratropical storm.

Tuesday, October 29, 1991

The previously stationary storm southeast of Nova Scotia continued to intensify. (See Figure 1d.) Surface pressure differential between the extratropical storm and the high pressure area over Canada created strong northeast winds which produced large ocean swells. As the extratropical storm intensified, Hurricane Grace became only a secondary contributor to the subsequent extraordinary sea conditions which were to persist over the next two days. Two ships located east of Georges Bank reported 40 and 43 foot (12 to 13 m) combined seas. National Oceanic and Atmospheric Administration (NOAA) wave data buoys reported wave heights of about 20 feet (6 m) and 12 feet (3.7 m) southeast of Nantucket and in Massachusetts Bay, respectively.

Wednesday, October 30, 1991

The strong northeast fetch of gale and storm force winds persisted throughout the night of the 30th, but eventually showed some signs of weakening. The storm continued moving westward, intensified further, and absorbed the remnants of Grace. At 0700 EST (1200 UTC), the storm had an extremely tight center with forecasted seas of 35 to 50 feet (10.7 to 15.2 m) within 300 nautical miles to the storm's north and west. (See Figure 1e.) Much of the damage along the southeastern New England coast occurred over the next several hours.

The duration and extent of this storm produced seas reported to be 40 to 78 feet high (12 to 23.8 m), with seas of 25 to 40 feet (7.6 to 12.2 m) closer to shore over the continental shelf. The Weather Service Meteorological Observatory in Chatham, Massachusetts recorded wind gusts greater than 60 miles per hour (mph) (26.8 meters/sec) for more than 15 straight hours and greater than 70 mph (31.3 m/s) for 6 hours. The strongest winds occurred near or just before the afternoon high tide. For the Boston, Massachusetts area, high tide occurred at approximately 4:33 P.M. (1633 EST, 2133 UTC), while in Chatham, high tide occurred at 5:05 P.M. (1705 EST, 2205 UTC). The combination of the strongest winds coinciding with high tide resulted in a tremendous build-up of seas offshore and helped produce extreme wave conditions. NOAA buoys reported wave heights up to 31 feet (9.4 m) and 25 feet (7.6 m) southeast of Nantucket (NOAA buoy 44008) and in Massachusetts Bay (NOAA buoy 44013), respectively.

Thursday, October 31, 1991

The extratropical system was now weakening. However, the system still generated northeast winds continuing to force tide levels well above normal. The towering coastal waves observed in previous days had diminished. The NOAA buoy southeast of Nantucket reported wave heights diminishing from 31 feet (9.4 m) in the morning to 11 feet (3.4 m) by the end of the day. The NOAA buoy in Massachusetts Bay recorded similar data of diminishing wave heights - from 30 feet in the early morning hours to 12 feet (3.7 m) before midnight. However, the movement of the low pressure area brought it over the Gulf Stream. (See Figure 1f.) This motion increased convection and the system acquired subtropical characteristics at 1300 EST (1800 UTC) on October 31.

Friday, November 1, 1991

Wind and sea conditions diminished considerably during the day due to the abatement of the large scale pressure gradients. However, the system moved over the warm Gulf Stream and reintensified. During the morning, satellite pictures showed that an eye was forming and the system was near hurricane intensity.

The cyclone moved east and then northeast during the day. (See Figure 1g.) Aircraft reconnaissance confirmed that the system was of hurricane intensity around 1900 EST (2400 UTC) 1 November. The radius of maximum winds was about 30 nautical miles, in contrast with the extratropical storm, which had a more uniform area of gale force winds extending well over 300 nautical miles with no clearly defined maximum wind radius. Although it was considered designating this storm a hurricane, it was felt that this designation could cause unnecessary confusion among the public, media and emergency management agencies.

Saturday, November 2, 1991

The storm continued in a northward track making landfall near Halifax, Nova Scotia at approximately 0900 EST (1400 UTC). By this time the storm system had characteristics of a tropical storm. The storm rapidly weakened and dissipated to the north of Nova Scotia, about 10 hours after landfall.

TABLE 1
Track of Halloween Storm
28 October - 2 November 1991

DATE / TIME EST	UTC	POSITION LAT. (N)	LONG. (W)	PRESSURE (mb)	WIND SPEED (mph)
28 / 1300	1800	44.0	59.0	1006	34.5
1900	2400	43.0	57.5	999	46.1
29 / 0100	0600	42.5	55.5	992	51.8
0700	1200	41.0	56.0	990	57.6
1300	1800	39.5	57.5	986	57.6
1900	2400	39.0	59.5	981	63.3
30 / 0100	0600	39.0	61.5	977	69.1
0700	1200	39.0	63.5	972	69.1
1300	1800	39.6	65.8	978	69.1
1900	2400	40.0	68.5	982	63.3
31 / 0100	0600	39.0	71.0	988	63.3
0700	1200	37.7	71.5	992	57.6
1300	1800	36.7	71.5	996	46.1
1900	2400	36.0	70.0	995	57.6
01 / 0100	0600	36.2	68.5	993	65.3
0700	1200	37.0	67.0	988	69.1
1300	1800	38.2	66.5	980	75.0
1900	2400	39.5	65.7	981	75.0
02 / 0100	0600	41.6	64.7	988	69.1
0700	1200	44.0	63.6	996	57.6
1300	1800	46.3	62.6	1005	34.5
1900	2400	48.5	61.0	----	----

(Source: National Weather Service)

EST: Eastern Standard Time
UTC: Universal Time Coordinates

III. BLIZZARD OF 1978 SUMMARY

The following is a brief description of the Blizzard of 1978. Further information and details can be found in the report "Blizzard of '78 - Coastal Storm Damage Study", published in February 1979 by the U.S. Army Corps of Engineers, New England Division.

The Blizzard of 1978 was the result of two low pressure areas combining off the coast of Cape Hatteras. The first was a low pressure area of warm moist air located near the Gulf Stream. The second was a more intense low pressure area moving south from Canada over the Great Lakes and containing very cold air at upper levels. The two systems combined and rapidly developed into an offshore gale on February 5, 1978. The gale then moved up the east coast parallel to the edge of the Continental Shelf.

The National Weather Service (NWS) declared the intensifying low pressure area to be a storm on the morning of February 6, 1978. By Monday evening, the storm was located east of New Jersey, and snow had begun accumulating in Boston. The slow moving storm stalled near Nantucket on the morning of February 7 due to an area of high pressure in Canada, but had again begun moving eastward by the afternoon. On Tuesday evening, the NWS had downgraded the storm to a gale and snowfall began tapering off. The storm moved west, making landfall on the Labrador, Canada coast and eventually dissipating by February 13.

In contrast to the Halloween Storm, the Blizzard was accompanied by large amounts of snowfall throughout the region. Therefore, damages and costs listed throughout this report for the Blizzard include snow removal efforts within the study area. Boston received about 27" (68.6 cm) of snow and Portland, Maine received almost 29" (73.7 cm) of snow.

Antecedent conditions did not have a significant effect on coastal damages which resulted from the Blizzard. According to the report "Blizzard of '78 - Coastal Storm Damage Study" any coastal flood damages experienced in January 1978 prior to the Blizzard were either repaired or insignificant in comparison to the damage caused by the Blizzard. The effects of two rainstorms and two snowstorms during the month of January prior to the Blizzard did not enhance or impede coastal flooding due to the Blizzard within the study area.

IV. STORM IMPACTS

The Halloween Storm produced extremely strong winds and excessive wave heights in New England. Winds between 30 mph (13.4 m/s) and 50 mph (22.4 m/s) were common at land based observation points, with gusts over 70 mph (31.3 m/s) reported. Large storm waves and surge were generated producing damage along the New England coast during the period of high tides. On October 30, during peak intensity of the storm, minimum central pressure was about 972 millibars (mb) or 28.3 inches of mercury (in. Hg), and estimated sustained winds at sea were near 69 mph (30.8 m/s). The storm caused phenomenal seas with some reported wave heights in the open Atlantic reaching 80 to 100 feet (24.4 to 30.5 m).

a. Storm Surge

Extratropical storms commonly occur along the northern portion of the east coast and are characterized by strong winds blowing from the northeast. These winds are primarily the result of interactions between low and high pressure areas and air/sea temperature differentials. Due to the immense, open areas of the ocean, large extratropical storms such as the Halloween Storm can be entirely situated over water, allowing a tremendous amount of energy to be transferred from the atmosphere to the water.

Storm surge is the amount of departure from the normal water level due to the action of storms and increases shoreward to a maximum level at the shoreline. The maximum surge is the highest level reached at a given location along the coast (neglecting the astronomical tide) and the peak surge is the highest maximum surge. Storm surge is produced when a horizontal flow of water in the form of surface currents is generated by the wind. As it approaches the coastline, this flow in the direction of the wind is affected by the shoaling bottom. The surface currents are impeded, causing a sustained increase in the level of waters over the Continental Shelf. Onshore winds can also augment the water levels at the edge of the Shelf.

Not only do wind and water interaction affect the determination of water levels, but decreases in atmospheric pressure also add to the height of storm surges. Barometric pressure is discussed further in a following section. Astronomical tides and the Earth's rotation can both cause changes in the level of the water during a storm. Precipitation preceding the storm, surface waves and associated wave setup, and other effects considered to be external to the system can all contribute to the magnitude of the storm surge. The Continental Shelf also causes a variance in surge depending on the width of the shelf at that specific location.

The shape of the coastline and the offshore bathymetry of the ocean are two of the many factors that affect the magnitude of the storm surge. The breadth and width of the storm surge depend on the size, intensity, the path relative to land, as well as the duration over the water and the speed of forward motion of the storm. The Halloween Storm was unusual in that it approached the New England area from the east. Due to the shoaling effect as the storm moves toward land, there is a piling up of waves nearshore. Abnormal rises in water level in nearshore regions will not only flood

low-lying terrain, but also provide a base on which larger waves can attack the upper portions of a beach and penetrate farther inland. This had occurred during the Halloween Storm where the large long period waves were carried further inland on higher water levels.

The storm surge effect probably better indicates the general severity of the event than stillwater levels. Graphs of observed stillwater tide levels and predicted astronomic tides, for October 29 through November 1, 1991, at Portland, Boston, Nantucket, and Woods Hole are shown in Figures 2-5, respectively. Maximum storm surges derived from comparison of observed and predicted tide levels are shown in Table 2. Historical data and estimated frequencies are also included for comparison.

TABLE 2

MAXIMUM STORM SURGES
& ESTIMATED FREQUENCY

STATION	OCTOBER 1991 DAY	SURGE (FT.)	FREQUENCY (YEARS)	HISTORICAL DATA DATE	SURGE (FT.)	FREQUENCY (YEARS)
Portland, ME	30	3.5	10	3/47	4.3	40
Boston, MA	30	5.1	90	11/45	4.9	80
Nantucket, MA	30	4.6	n/a	—	—	—
Woods Hole, MA	30	4.4	n/a	9/44	6.7	n/a

n/a: not available.

The storm surge associated with the Blizzard of 1978 was 4.4' (1.34 m) at Boston, Massachusetts and 3.0' (0.91 m) at Portland, Maine. These elevations are equivalent to return periods of approximately 35 years and 4 years at Boston and Portland, respectively. This is in contrast to return periods of 90 years and 10 years at Boston and Portland, respectively for the Halloween Storm.

The storm surge data is one parameter which shows the extreme severity of the Halloween event, particularly in the area between Boston and Nantucket. At Boston, the surge is the greatest of modern record, surpassing the previous record occurring during the November 1945 "northeaster" and over 1.0' (0.30 m) higher than the surge which had occurred during the Blizzard. Historic storm surge data and frequencies for Portland and Boston were derived from "Criteria for a Standard Project Northeaster for New England North of Cape Cod", U.S. Weather Bureau, 1964, supplemented by "A Tide Climatology for Boston, Massachusetts", National Weather Service, 1982. No comparative data are available for Nantucket. At Woods Hole, maximum surges are associated with hurricanes. Historic surge at Woods Hole was taken from "Characteristics of the Hurricane Storm Surge", U.S. Weather Bureau, 1963.

b. Astronomic Tides

The following is a discussion and comparison of the tide levels and cycles occurring during both the Halloween Storm and the Blizzard of 1978.

Blizzard of 1978

The normal astronomic tide levels for the New England area on the night of February 6 and the morning of February 7, 1978 were expected to be unusually high, regardless of the Blizzard of 1978's effects. This was due to the following factors:

1) A new moon (syzygy) resulting in spring tides,

2) The location of the moon's orbit, which was at its perigee (closest point of the orbit to the earth), resulting in a stronger influence on tides and a greater tidal range (perigean tides), and

3) A nodal tide producing a greater range of tidal elevations than would otherwise be expected. The nodal tide is the result of the orientation of the elliptical orbits of the earth and moon and the strength of the sun and moon's attractive forces. A nodal tide occurs once every 18.6 years and the nodal tide cycle peaked in early February, 1978.

Therefore, the normal astronomic tide cycle for February 6 and 7 was influenced by a perigean spring tide during the peak of the nodal tide cycle. Coincidently, the Blizzard of 1978 occurred at the same time creating abnormally high water levels.

Halloween Storm

The Halloween Storm occurred simultaneously with a period of normal astronomic tides sparing many coastal areas even greater damage than had occurred. Had the Halloween Storm arrived 5 days earlier during a period of high spring astronomic tides, observed stillwater levels could have been approximately 1.5' (0.46 m) higher. However, the Halloween Storm coincided with the moon in the last quarter (neap), coming less than one week after spring tides caused by a full moon (syzygy) which are the highest tides of the month. The storm also arrived after perigean tides (when the moon's orbit is closest to the earth) occurred on October 27.

A comparison of the normal tidal cycles between February 1978 and October/November 1991 reveals that the predicted high tide elevations for February 1978 at Boston and Portland were about 1.8' (0.55 m) and 1.3' (0.40 m) higher, respectively. Hypothetically, had the Halloween Storm coincided with the highest tides of October 1991, the predicted high tide elevations at this time would have still been up to 1.0' (0.30 m) less than the predicted high tides of February 1978.

c. Water Levels

Unusually high stillwater levels were observed during the storm at National Ocean Service (NOS) tide gauges along the New England coast. Stations of particular interest are included in Table 3. Also included for comparison are observed historical maximum stillwater levels, along with estimated frequencies. At Woods Hole, historic maximum flooding has been caused primarily by hurricanes rather than extratropical storms (northeasters).

TABLE 3

OBSERVED MAXIMUM STILLWATER
TIDE LEVELS
& ESTIMATED FREQUENCY

STATION	OCTOBER 1991 DAY	LEVEL (FT., NGVD)	FREQUENCY (YEARS)	HISTORICAL MAXIMUM DATE	LEVEL (FT., NGVD)	FREQUENCY (YEARS)
Portland, ME	30	8.2	4	2/78	9.6	133
Boston, MA	30	9.4	17	2/78	10.3	100
Nantucket, MA	30	6.3*	n/a	1/87	4.8*	n/a
Woods Hole, MA	31	4.8	4	9/38	10.5	77

* Datum is local mean sea level since NGVD is not available on Nantucket.

Previous Pearson Type III frequency analysis, conducted by the New England Division, for Portland, Boston, and Woods Hole (respective periods of record 1912-1987, 1848-1987, and 1933-1987), were used to estimate frequencies in Table 3. Frequency analysis has not been conducted for Nantucket by the Corps due to the shorter period of record at that location (1965-present), the presence of at least 12 incomplete years of data, and the absence of a fixed geodetic datum. However, the 1991 stillwater tide event is the highest of the 27 year record at Nantucket, which indicates it is likely rarer than a 30-year event.

Review of Table 3 reveals that the frequency of ocean stillwater for this event is probably not a true indicator of the storm's overall severity. Stillwater is a measure of the ocean level with wave effects minimized. Tidal gages are generally located in low wave environments and wave effects are dampened out by use of a wet well. Stillwater tide readings are comprised primarily of the astronomic tide, wind setup, and barometric effects. Large, long period waves may cause flooding from wave setup, runup, and overtopping which is higher than the true ocean stillwater level. Conversely, restrictive tidal inlets can result in interior flooding much lower than ocean stillwater. It is apparent from the observed coastal damage and water levels that extreme wave action was the primary flood producing factor. This is because the observed water levels were less than a 20-year event, while the measured wave heights and wave periods (e.g., 20 seconds) were extreme for this storm. For example, the wave heights measured at Buoy 44013 in Massachusetts Bay were the highest ever recorded since the station was established in 1984.

Had the Halloween Storm coincided with the highest predicted tide elevations for October 1991 in combination with the actual storm surge created by the Halloween Storm, possible maximum water levels could have been 11.2' (3.41 m) NGVD at Boston, and 9.1' (2.77 m) NGVD at Portland. This hypothetical stillwater level at Boston is almost 1.0' (0.30 m) higher than what had occurred in 1978. The hypothetical stillwater level at Portland would still have been 0.5' (0.15 m) less than the Blizzard. These hypothetical values can be compared with those in Table 3. These hypothetical stillwater elevations also assume that the maximum storm surge occurs at the highest tide of the storm's duration. While this is not always true (maximum surge during the Halloween Storm actually occurred around the lower portions of the tidal cycle), it shows that the Halloween Storm was capable of producing the highest water levels ever to have historically occurred in Boston. Had the storm arrived during either the spring tides or the perigean tides, coincident with peak storm surge occurring at the higher portions of the tidal cycle, the Halloween Storm could have produced the most extreme coastal damages ever experienced throughout New England.

d. Winds

Extremely strong winds are the primary factor in producing tidal surge and intense wave action. Although it is the winds far out to sea that primarily generate the storm conditions affecting the coast, reliable wind data in the open ocean is generally not available. Therefore, it is useful to examine wind data from land based coastal meteorological stations of the National Weather Service. Table 4 summarizes wind data for the Halloween Storm and provides historical comparisons. Highest winds for the 1991 storm appear to be at Chatham and Nantucket, Massachusetts. A greater northerly wind component is evidenced at Chatham. Portland winds were similar to those of the Blizzard of 1978, although from a more northerly direction. Winds at Boston did not reach levels recorded in 1978. Extreme winds at Chatham and Nantucket during the 1944 hurricane were not matched by the 1991 northeaster.

TABLE 4

MAXIMUM STORM WIND GUSTS
1-MINUTE AVERAGE & DIRECTION

STATION	30 OCTOBER 1991 GUST (MPH)	1-MIN. AVG. (MPH)	DIR.	HISTORICAL DATA DATE	1-MIN. AVG. (MPH)	DIR.
Portland, ME	53	30	N	2/78	29	NE
Boston, MA	55	37	NE	2/78	61	NE
				11/45	63*	NE
Nantucket, MA	—	52	NNE	9/44	85	—
Woods Hole, MA	64	47	NE	9/44	57*	SW

* Value shown is a 5-minute average.

Hourly wind data throughout the 1991 storm for Portland, Boston, Chatham, and Nantucket have been plotted on Figures 6 through 9, respectively. These figures show wind gusts, 1-minute average speed, and direction. For ease of presentation, the wind direction is shown on the lower portion of each graph and is recorded in tens of degrees clockwise (CW) from north (i.e., east of north is 1, and west of north is 35). These time histories show the storm intensifying and peaking on the 30th, and then gradually diminishing in strength.

e. Barometric Pressure

Barometric pressure can be an important parameter in causing storm surge. A "rule-of-thumb" is that a sudden drop in barometric pressure of 1 inch of mercury (Hg) will promote ocean level to rise about 1 foot. The Halloween Storm had a large surge associated with it. A peculiarity of this event was that the pressure at coastal meteorological stations, although dropping significantly during the storm, were considered quite high. Figures 10 through 13 show station pressure throughout the storm for Portland, Boston, Chatham, and Nantucket, respectively. During the height of the storm on the 30th, these stations had readings of about 30.1, 30.0, 30.0, and 29.8 inches Hg, respectively. Conversely, pressure at the storm center was about 28.3 inches Hg. This difference reflects the great pressure gradients and associated high winds along the New England coast.

f. Erosion

Erosion of the New England coast due to the Halloween event depended on numerous factors involving the severity of the wave climate, surge levels, duration of the storm, and the coastal geomorphology. An extensive analysis of erosion is beyond the scope of this study and requires site-specific information and data collection.

Extreme events such as the Halloween Storm can have significant short and long term effects on the profile of a beach. However, the magnitude of a storm does not alone determine the amount of erosion, accretion or other geomorphic changes which may occur. Table 5 identifies a number of variables which can be qualitatively evaluated to determine whether a specific area has a tendency to erode.

TABLE 5

FACTORS INFLUENCING EROSION
CAUSED BY STORMS

Main Factors	Sub-Factors	Increased Tendency Toward Erosion
Storm Processes	Wind Velocity	High
	Wind Direction	Variable
	Wave Height	High
	Wave Period	Low
	Wave Steepness	High
	Longshore Current	High
	Storm Duration	High
Beach Characteristics	Sediment Size	Low (to silt size)
	Degree of Lithification	Low
	Morphology - slope	High
Water Level	Tide Stage	High
	Storm Surge	High

(Ref. Shore Protection Manual, Vol. 1)

Example 1: Erosion tends to increase when the wave height is high, wave period is low, and beach slope is high.

Example 2: Erosion tends to increase if sediment size is low (small grain size), and the storm surge and duration are both high.

Most storms and associated high energy wave climates move large amounts of material both offshore and alongshore within the littoral environment. Subsequent lower energy or average wave climates tend to restore this material to the beach face over time if the material is available in the littoral zone. However, storm waves are capable of moving material into, 1) deeper depths offshore where material can not be recovered by normal wave action, or 2) landward by overwashing the beach. Both result in a loss of material from the littoral environment. Moreover, areas of the shoreline which are armored (seawalls, revetments) may prevent new littoral material from entering the system.

The amount of material moved alongshore is dependent on the direction of storm waves and their angle of approach to the shoreline. If the direction of longshore transport caused by the storm is opposite to the net direction of transport, the eroded material will probably return to the affected beach resulting in little permanent change. However, if the direction of transport is the same before, during, and after the storm, then it is possible that the material removed by the storm will not be available to eventually restore the beach to its original condition. This can only be determined on a site specific basis.

Erosion and recession of bluffs, scarps, or cliffs are directly related to the type of landform seaward of them. Beaches have the natural ability to eventually restore themselves by obtaining material stored in dunes, backshore bluffs, or offshore sandbars. However, bluffs do not have these restoration mechanisms and will continually recede until a more stable position is attained. This is evident at certain areas of the east facing shorelines of Cape Cod (Truro) and Nantucket (Sankaty).

There are various reports of dune and beach recession ranging from a few feet to 30' (9.1 m) throughout the study area. Dunes in Saco, Maine reportedly retreated about 5' (1.5 m), and the beach berm at Shingle Beach in Scituate was lowered 4'-6' (1.2 - 1.8 m). Beach erosion at Springhill Beach in Sandwich averaged about 5'-10' (1.5 - 3.0 m) with certain areas eroding up to 25' (7.6 m). At Chatham, the area in front of the Coast Guard station experienced severe erosion and bluff recession up to 20' (6.1 m).

At the Cape Cod National Seashore numerous staircases leading to the beach were destroyed. At Highland Lighthouse in Truro, there was about 10' (3.0 m) of bluff recession. National Park Service personnel reported that Marconi Beach and the Nauset Light area experienced approximately 10'-15' (3.0 - 4.6 m) of bank erosion and Coast Guard Beach in Eastham experienced up to 20'-30'(6.1 - 9.1 m) of erosion. Beach erosion of the east facing shoreline of Nantucket from Codfish Park to Sankaty Head measured between 20' (6.1 m) and 30' (9.1 m), and bluff recession was between 10'-15' (3.0 - 4.6 m). Third Point to Coatue Point, which faces Nantucket Sound, experienced a 7'-12' (2.1 - 3.7 m) reduction in dune height.

This study did not attempt to quantify either the rates of erosion or the volumes of material lost within the study area. However, utilizing the results of the wave and water level hindcast and comparing them with geomorphic characteristics of the coast could lead to identifying sites where erosion has the potential to cause significant damages from future extratropical events. Furthermore, the hindcast results can also be used as an aid in determining erosion rates and material losses due to extratropical storms through the use of modeling methodologies such as SBEACH. SBEACH is a two-dimensional beach profile model which predicts storm-induced beach erosion and post-storm recovery. It can also be used to predict the short-term response of beach fills to storms.

g. Storm Damage

Commercial and residential structures, seawalls, revetments, and other shore protection structures, roads, utilities, beaches and natural habitats were all subjected to the destructive forces of the Halloween Storm. These damages included private and public property affected by high water levels and large waves. A descriptive account of the damages and erosion throughout the study area is provided in Appendix E - Storm Damage. Although this study is limited to the storm's effects on the New England coast, damages occurred along the entire eastern seaboard. According to the NOAA technical memorandum "Effects of The Late October 1991 North Atlantic Extra-Tropical Storm on Water Levels - Data Report", issued in January 1992, significant storm surge was observed as far south as South Carolina and extreme wave and surf conditions farther south along the Florida coast.

Even though the surge levels were minimal in Florida, NOAA's Lake Worth Pier gaging station was destroyed by severe wave conditions which resulted in equipment being recovered up to a mile south of the station.

A NOAA Disaster Survey Team toured the New England area and other portions of the east coast following the storm event. According to their findings "...Without a doubt, the east coast and coincident islands of Massachusetts, being closest to and directly downfetch from the strongest core of the storm, took the most severe pounding...", and "...Across coastal sections of Maine and New Hampshire, the most significant damage was limited to those communities which received direct wave battering from the ocean."

The effects of the Halloween Storm resulted in losses, damage, and erosion even after the storm had abated. For example, the Mid-Atlantic coast was subjected to another coastal storm about a week after the Halloween Storm. Structures and dunes previously weakened by the Halloween Storm were destroyed or severely damaged by this second event. In Massachusetts, the Nantucket shoreline in the vicinity of Siasconset and Codfish Park was subjected to further damage and loss of structures from a severe northeaster in December 1992. Although this occurred over a year later than the Halloween Storm, these structures would not have been as vulnerable had the Halloween Storm not caused significant amounts of erosion and recession of beaches, dunes, and bluffs.

Damage data and information concerning losses attributed to the storm were obtained primarily from the Federal Emergency Management Agency's (FEMA) Damage Survey Reports (DSR's), and claims data obtained from the Federal Insurance Administration (FIA). Other descriptive information was obtained from Corps of Engineers files, various affected communities and state officials. This study is not an all inclusive attempt to identify and document damages and losses due to the Halloween Storm. The data compiled for this investigation is provided only for a comparison analysis between the Halloween Storm and similar data which was compiled for the Blizzard of 1978, and also to identify trends correlating the offshore wave and water level climate with damages occurring onshore.

h. Economic Assessment

An economic assessment has been conducted summarizing insurance claims payments and economic losses within coastal communities from Nantucket, Massachusetts to Portland, Maine for both the Blizzard of 1978 and the Halloween Storm of 1991. Tables 6-9 show the various claim payments and economic losses associated with each storm. They include public, non-profit, and private reimbursements made by the Federal Emergency Management Agency (FEMA) and the Federal Insurance Administration (FIA).

This funding information is presented on a regional basis as shown on Figure 14 - Study Area Location Map. The regions are based primarily on geographic considerations such as exposure to open ocean and angle of shoreline. The regions are: Region I which is Nantucket; Region II which covers from Chatham to Provincetown (essentially the east facing shore of Cape Cod); Region III covers the north facing shorelines of towns in Cape Cod Bay (Brewster to Bourne); Region IV from Plymouth to Hull (exposure to

the northeast); Region V from Hingham to the south facing shoreline of Gloucester; Region VI from Rockport, Massachusetts to Kennebunk, Maine, including the north facing shoreline of Gloucester, Massachusetts, and Region VII from Kennebunkport to Portland, Maine.

An evaluation of contrasts between the 1978 and 1991 storms among the various damage categories for specific towns has not been made. Specific information as to the extent and location of damages is required for this type of evaluation. However, on a regional scale, differences among the various categories are shown in Table 6 on the next page.

Table 6 summarizes Federal Disaster Assistance Administration (FDAA) funding to municipalities for the Blizzard of 1978 and FEMA funding for the Halloween Storm, respectively. This funding is based on damage surveys of each municipality accomplished by FEMA. The following categories are used:

Debris Clearance - Includes public roads and rights-of-way and structure demolition.

Protective Measures - Includes protective measures for life, safety, health, and property.

Road Systems - Includes streets, traffic control, bridges, and culverts.

Water Control Facilities - Includes dikes, dams drainage channels, and levees.

Public Buildings - Includes buildings and equipment, supplies and inventory, and vehicles.

Public Utilities - Includes water, sanitary sewerage, storm drainage, and light and power.

Other - This includes items not in the above categories and park and recreational facilities.

Based on the information in Table 6 which was derived from Damage Survey Reports from FEMA, Region I was not as severely affected by the Blizzard as it was by the Halloween Storm. Within Region II (Chatham to Provincetown), the largest differences are within the "Debris Clearance" and "Other" categories. For Region III, the area within Cape Cod Bay is essentially protected by the outer "arm" of Cape Cod, the largest difference was in the "Water Control Facilities" category, where there was about $65,000 more in payments made as a result of the Blizzard of 1978. Region IV, an area traditionally hard hit by extratropical storms, shows a large difference in total funding to municipalities. There was about $18.5 million in funding attributed to the Blizzard of 1978 and only about $4.3 million for the Halloween Storm. This difference can be largely attributed to the funding for water control facilities, however, without an in-depth analysis of damages within the communities in this region, it is only speculation as to why there was so great a difference. Within Region V, the greatest differences are exhibited in the "Water Control Facilities", "Public Utilities", and "Other" categories. Region VI exhibited over $1 million

more in damage as a result of the Halloween Storm, with the largest difference being in the "Debris Clearance" category. Region VII data is derived from a single community and may not be representative of differences in funding to the municipalities in this region. Therefore, no comparisons have been made.

TABLE 6

REGIONAL FUNDING
TO MUNICIPALITIES
(1991 Price Levels)

	Category (Thousands $)						
Region	Debris Clear.	Prot. Meas.	Road Systems	Water Cntrl.	Pub. Bldg.	Pub. Util.	Other
I 1978	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1991	9.3	14.7	7.3	0.0	24.0	4.6	90.4
II 1978	16.9	15.1	46.7	86.8	1.1	2.8	88.3
1991	97.5	89.3	10.2	0.0	10.2	5.1	638.2
III 1978	57.2	63.7	74.2	74.7	3.4	26.0	85.4
1991	11.4	23.7	20.2	9.0	1.0	1.0	71.9
IV 1978	1,105.1	909.2	1,450.5	12,442.2	55.5	1,802.0	740.2
1991	1,035.2	674.2	609.4	654.4	66.8	110.7	1,117.9
V 1978	310.0	474.3	406.3	3,297.4	146.7	828.3	1,140.0
1991	455.8	233.1	206.0	1,737.5	55.8	42.5	320.9
VI 1978	178.0	128.3	278.9	1,126.0	25.2	40.5	75.0
1991	327.3	279.1	618.9	1,491.0	3.7	86.2	153.4
VII 1978	71.9	6.3	0.0	18.9	6.8	0.0	0.0
1991	28.5	2.3	0.0	37.6	0.0	0.0	0.0

Tables 7 and 8 summarize Federal Disaster Assistance Administration (FDAA) funding to municipalities for the Blizzard of 1978 and FEMA funding for the Halloween Storm, respectively. This funding is based on damage surveys of each municipality accomplished by FEMA.

Table 7 data was obtained from a previous Corps of Engineers publication, Blizzard of '78 Coastal Storm Damage Study, February 1979. This information had not been compiled for most of the communities in Maine and data relating to the Blizzard of 1978 was not obtainable. The information from Damage Survey Reports may be obtainable through contacting each community and searching FEMA archives, however, this was not possible within the scope of this study. The dollar amounts have been updated to 1991 price levels by multiplying by an average of the Construction Cost Index (CCI) appearing in the Engineering Review and the Implicit Price Deflator for gross domestic product published in the Survey of Current Business by the U.S. Department of Commerce. The data in Tables 7 and 8 are directly comparable. The funding amounts in Table 7 under the "Debris Removal" category for the Blizzard includes snow removal which was not required during the Halloween Storm.

The National Flood Insurance Program (NFIP) was initiated in 1968 and expanded in 1973. Under this program, the Federal government made flood insurance available to communities with existing property in flood hazard areas in return for enactment and enforcement of floodplain management regulations designed to reduce future flood losses. In 1983, the FIA began the "Write-Your-Own" (WYO) program. Under this initiative, private insurance companies are permitted to sell and service flood insurance under their own names. Eighty percent of flood insurance is presently sold by insurance companies participating in this program.

Table 9 contains direct and WYO insurance claim data obtained from the FIA under the NFIP. (The WYO program was not in effect in 1978.) The 1978 dollar amounts have been updated to 1991 price levels using the methodology previously described. For the coastal communities within the study area there were over 2,200 claims from the Blizzard and over 4,800 for the Halloween Storm. These claims account for approximately $35,730,000 and $82,300,000 within the study area for the Blizzard and Halloween events, respectively. Some claims did not result in payments, therefore, the "average per claim" shown in Table 9 is a low estimate of the actual dollars paid per claim.

The number of policies issued and in effect during the Blizzard of 1978 and the Halloween Storm is also a factor contributing to the number of claims and, hence, the total payments made on those claims. This information and data should be investigated on a site-specific basis when comparing damages and losses between specific storm events.

This information is not meant to represent a comprehensive data base of financial losses associated with these two storms. It is meant only as a reference to provide comparisons to similar data compiled for the

TABLE 7

FDAA FUNDING TO MUNICIPALITIES
BLIZZARD OF 1978

1991 Price Levels

	COMMUNITY	DEBRIS CLEARANCE	PROTECTIVE MEASURES	ROAD SYSTEMS	WATER CONTROL FACILITIES	PUBLIC BUILDINGS	PUBLIC UTILITIES	OTHERS	TOTAL
REGION I	NANTUCKET	0	0	0	0	0	0	0	0
REGION II	CHATHAM	0	0	0	0	0	0	0	0
	PROVINCETOWN	6,200	14,800	0	0	0	0	63,500	84,600
	TRURO	0	0	16,500	86,800	0	0	0	103,400
	WELLFLEET	0	0	30,200	0	0	2,800	3,000	36,000
	EASTHAM	1,800	300	0	0	1,100	0	18,500	21,600
	ORLEANS	8,900	0	0	0	0	0	3,300	12,100
REGION III	BREWSTER	10,100	0	4,800	0	0	26,000	0	41,000
	DENNIS	14,900	60,500	69,400	8,800	0	0	9,600	163,200
	YARMOUTH	0	0	0	500	0	0	50,600	51,100
	BARNSTABLE	600	3,200	0	36,300	3,400	0	2,000	45,500
	SANDWICH	0	0	0	0	0	0	21,500	21,500
	BOURNE	31,600	0	0	29,100	0	0	1,700	62,400
REGION IV	PLYMOUTH	23,600	70,200	70,100	1,351,300	200	19,000	268,700	1,803,200
	KINGSTON	0	64,000	0	5,700	0	0	5,400	75,100
	DUXBURY	37,900	1,600	144,700	400	0	0	0	184,600
	MARSHFIELD	135,000	184,600	759,000	838,700	5,200	118,900	0	2,041,300
	SCITUATE	748,600	414,100	325,900	9,076,300	13,000	344,300	167,900	11,090,100
	HULL	158,600	144,000	150,800	1,080,200	31,900	1,300,400	79,800	2,945,600
	COHASSET	1,400	30,700	0	89,600	5,200	19,400	218,400	364,600
REGION V	HINGHAM	0	11,700	5,700	0	6,900	74,200	0	98,500
	WEYMOUTH	4,400	0	0	0	0	4,400	0	8,800
	BRAINTREE	0	0	0	0	0	7,200	2,500	9,600
	QUINCY	8,000	0	24,700	43,200	7,600	5,400	38,700	127,600
	BOSTON	41,700	120,400	0	865,600	0	185,200	456,800	1,669,700
	WINTHROP	77,900	0	35,400	32,300	19,600	23,800	33,200	222,200
	REVERE	66,800	195,100	163,300	4,400	1,500	226,800	36,100	693,900
	LYNN	0	0	900	25,400	0	0	2,100	28,400
	NAHANT	35,700	66,700	14,400	736,100	45,900	183,200	135,800	1,217,600
	SWAMPSCOTT	13,600	15,600	20,600	268,800	500	9,800	59,700	388,800
	MARBLEHEAD	10,100	600	1,400	419,700	1,200	92,400	128,600	654,000
	SALEM	24,700	5,000	6,900	21,000	700	4,300	137,500	200,100
	BEVERLY	1,500	59,200	11,200	98,800	16,000	9,100	66,600	262,400
	MANCHESTER	4,100	0	108,400	432,300	45,500	0	0	590,300
	GLOUCESTER (S)	21,500	0	13,400	349,800	1,250	2,450	42,350	430,700
REGION VI	GLOUCESTER (N)	21,500	0	13,400	349,800	1,250	2,450	42,350	430,700
	ROCKPORT	47,500	9,700	28,600	763,500	16,300	6,900	12,900	885,500
	ESSEX	0	4,900	0	3,900	0	0	0	8,800
	IPSWICH	18,200	0	2,200	0	0	15,400	0	35,700
	ROWLEY	0	0	0	0	0	0	0	0
	NEWBURY	28,100	1,400	148,300	0	0	0	0	177,800
	NEWBURYPORT	22,600	0	0	0	0	0	0	22,600
	SALISBURY	12,200	7,300	60,800	0	0	0	8,500	88,800
	SEABROOK	0	0	0	0	0	1,400	0	1,400
	HAMPTON	3,700	90,600	11,500	0	600	1,200	4,000	111,700
	NORTH HAMPTON	500	2,400	0	0	0	0	0	2,900
	RYE	13,500	4,500	12,700	0	4,000	0	0	34,700
	PORTSMOUTH	0	0	0	0	0	13,100	0	13,100
	NEW CASTLE	300	7,500	1,400	0	0	0	0	9,200
	WELLS	9,900	0	0	8,800	3,000	0	7,200	29,000
REGION VII	SACO	71,900	6,300	0	18,900	6,800	0	0	103,900
	TOTAL	1,739,100	1,596,900	2,256,600	17,046,000	238,600	2,699,500	2,128,800	27,705,300

TABLE 8

FEMA FUNDING TO MUNICIPALITIES
HALLOWEEN STORM OF 1991

1991 Price Levels

	COMMUNITY	DEBRIS CLEARANCE	PROTECTIVE MEASURES	ROAD SYSTEMS	WATER CONTROL FACILITIES	PUBLIC BUILDINGS	PUBLIC UTILITIES	OTHERS	TOTAL
REGION I	NANTUCKET	9,300	14,700	7,300	0	24,000	4,600	90,400	150,300
REGION II	CHATHAM	87,430	66,500	10,200	0	8,600	5,100	594,800	772,630
	PROVINCETOWN	0	0	0	0	0	0	0	0
	TRURO	0	0	0	0	0	0	0	0
	WELLFLEET	2,300	8,800	0	0	1,000	0	1,000	13,100
	EASTHAM	2,800	4,200	0	0	0	0	0	7,000
	ORLEANS	5,000	9,800	0	0	600	0	42,400	57,800
REGION III	BREWSTER	900	1,800	8,600	0	1,000	0	0	12,300
	DENNIS	5,000	7,600	10,200	1,200	0	0	2,200	26,200
	YARMOUTH	0	0	0	0	0	0	49,800	49,800
	BARNSTABLE	1,800	5,700	0	0	0	1,000	2,500	11,000
	SANDWICH	0	8,600	1,400	0	0	0	12,300	22,300
	BOURNE	3,700	0	0	7,800	0	0	5,100	16,600
REGION IV	PLYMOUTH	32,280	53,500	1,800	0	1,500	0	72,900	161,980
	KINGSTON	400	7,700	0	27,100	1,000	0	12,400	48,600
	DUXBURY	367,660	504,900	156,100	4,600	17,500	19,400	972,800	2,042,960
	MARSHFIELD	118,600	22,700	39,900	0	1,000	0	0	182,200
	SCITUATE	271,400	53,000	56,000	586,500	500	59,500	45,100	1,072,000
	HULL	226,824	23,200	354,100	2,100	45,300	30,700	13,300	695,524
	COHASSET	18,000	9,200	1,500	34,100	0	1,100	1,400	65,300
REGION V	HINGHAM	0	3,200	0	0	0	12,200	0	15,400
	WEYMOUTH	34,500	10,000	7,500	6,800	8,600	0	8,700	76,100
	BRAINTREE	0	0	0	0	0	0	0	0
	QUINCY	58,200	39,400	0	271,400	18,200	0	2,100	389,300
	BOSTON	5,300	0	0	269,300	0	0	0	274,600
	WINTHROP	65,700	32,700	7,300	243,400	0	18,600	17,200	384,900
	REVERE	65,900	57,100	0	14,000	2,200	0	0	139,200
	LYNN	0	9,300	0	7,700	0	800	100,600	118,400
	NAHANT	142,100	28,200	0	182,800	0	300	48,000	401,400
	SWAMPSCOTT	14,600	8,100	700	44,800	400	0	2,200	70,800
	MARBLEHEAD	15,800	10,100	24,900	82,700	19,500	10,600	36,300	199,900
	SALEM	2,700	17,900	0	48,100	600	0	77,700	147,000
	BEVERLY	25,800	2,700	800	153,000	0	0	900	183,200
	MANCHESTER	0	4,500	36,500	99,200	6,300	0	0	146,500
	GLOUCESTER (S)	25,200	9,900	128,250	314,300	0	0	27,200	504,850
REGION VI	GLOUCESTER (N)	25,200	9,900	128,250	314,300	0	0	27,200	504,850
	ROCKPORT	43,100	13,100	57,200	254,900	1,000	4,000	44,800	418,100
	ESSEX	600	1,800	0	0	300	0	0	2,700
	IPSWICH	12,740	2,500	0	0	0	0	0	15,240
	ROWLEY	0	0	0	0	0	1,600	1,800	3,400
	NEWBURY	8,900	2,400	76,800	0	0	6,300	900	95,300
	NEWBURYPORT	3,400	500	12,100	0	0	0	2,800	18,800
	SALISBURY	58,460	11,500	107,900	0	2,400	0	6,800	187,060
	SEABROOK	2,600	3,700	0	0	0	0	0	6,300
	HAMPTON	35,900	10,500	0	0	0	0	19,200	65,600
	NORTH HAMPTON	0	600	8,200	0	0	0	0	8,800
	RYE	31,700	900	26,400	0	0	3,000	0	62,000
	PORTSMOUTH	0	0	0	0	0	0	0	0
	NEW CASTLE	2,900	300	0	0	0	0	4,200	7,400
	YORK	27,000	13,700	115,300	15,800	0	71,300	44,800	287,900
	WELLS	43,700	6,500	16,000	0	0	0	0	66,200
	KENNEBUNK	31,100	201,200	70,700	906,000	0	0	900	1,209,900
REGION VII	SACO	28,500	2,300	0	37,600	0	0	0	68,400
	TOTAL	1,965,000	1,316,400	1,471,900	3,929,500	161,500	250,100	2,392,700	11,487,100

TABLE 9

DIRECT & WYO CLAIMS AND PAYMENTS BY REGION AND COMMUNITY

1991 Price Levels

			1978			1991		
			Number Of Claims	Amount Paid	Average Per Claim	Number Of Claims	Amount Paid	Average Per Claim
REGION I	1	NANTUCKET	2	$2,549	$1,275	143	$4,785,081	$33,462
REGION II	2	CHATHAM	6	$26,758	$4,460	71	$1,161,766	$16,363
	3	PROVINCETOWN	10	$26,765	$2,677	7	$49,044	$7,006
	4	TRURO	0	$0	$0	0	$0	$0
	5	WELLFLEET	9	$67,165	$7,463	0	$0	$0
	6	EASTHAM	10	$42,986	$4,299	7	$122,791	$17,542
	7	ORLEANS	6	$4,432	$739	17	$505,380	$29,728
REGION III	8	BREWSTER	0	$0	$0	3	$25,117	$8,372
	9	DENNIS	13	$38,347	$2,950	11	$29,669	$2,697
	10	YARMOUTH	13	$15,435	$1,187	5	$20,199	$4,040
	11	BARNSTABLE	5	$101,251	$20,250	17	$2,025,389	$119,141
	12	SANDWICH	6	$7,066	$1,178	57	$630,796	$11,067
	13	BOURNE	4	$4,315	$1,079	1	$0	$0
REGION IV	14	PLYMOUTH	39	$736,726	$18,890	118	$2,327,746	$19,727
	15	KINGSTON	2	$9,592	$4,796	2	$6,482	$3,241
	16	DUXBURY	38	$683,433	$17,985	92	$2,693,252	$29,274
	17	MARSHFIELD	161	$1,585,987	$9,851	441	$8,739,320	$19,817
	18	SCITUATE	571	$14,419,195	$25,253	877	$23,316,509	$26,587
	19	HULL	320	$4,861,702	$15,193	521	$4,861,645	$9,331
	20	COHASSET	10	$103,831	$10,383	31	$617,249	$19,911
REGION V	21	HINGHAM	12	$133,707	$11,142	19	$125,427	$6,601
	22	WEYMOUTH	12	$92,678	$7,723	43	$269,150	$6,259
	23	BRAINTREE	1	$945	$945	2	$41,676	$20,838
	24	QUINCY	126	$1,015,400	$8,059	196	$1,515,756	$7,733
	25	BOSTON	8	$332,998	$41,625	8	$32,915	$4,114
	26	WINTHROP	145	$1,156,873	$7,978	286	$2,266,369	$7,924
	27	REVERE	289	$4,603,051	$15,928	421	$5,117,394	$12,155
	28	LYNN	1	$8,904	$8,904	7	$95,855	$13,694
	29	NAHANT	67	$973,238	$14,526	109	$2,857,468	$26,215
	30	SWAMPSCOTT	33	$741,396	$22,467	63	$1,410,601	$22,390
	31	MARBLEHEAD	34	$460,338	$13,539	48	$957,644	$19,951
	32	SALEM	7	$47,459	$6,780	23	$197,623	$8,592
	33	BEVERLY	9	$78,443	$8,716	18	$197,713	$10,984
	34	MANCHESTER	3	$149,568	$49,856	25	$474,058	$18,962
	35	GLOUCESTER (S)	32	$681,844	$21,308	68	$2,795,395	$41,109
REGION VI	36	GLOUCESTER (N)	10	$52,945	$5,295	12	$128,343	$10,695
	37	ROCKPORT	37	$569,300	$15,386	134	$2,798,164	$20,882
	38	ESSEX	6	$80,984	$13,497	7	$210,352	$30,050
	39	IPSWICH	3	$40,398	$13,466	7	$139,214	$19,888
	40	ROWLEY	0	$0	$0	0	$0	$0
	41	NEWBURY	69	$394,777	$5,721	41	$265,643	$6,479
	42	NEWBURYPORT	68	$533,767	$7,850	45	$218,446	$4,854
	43	SALISBURY	44	$843,104	$19,161	116	$2,057,006	$17,733
	44	SEABROOK & SEABR. BEA	0	$0	$0	10	$29,812	$2,981
	45	HAMPTON	0	$0	$0	134	$1,088,708	$8,125
	46	NORTH HAMPTON	0	$0	$0	15	$118,901	$7,927
	47	RYE	0	$0	$0	75	$578,228	$7,710
	48	PORTSMOUTH	0	$0	$0	1	$2,574	$2,574
	49	NEW CASTLE	0	$0	$0	1	$4,683	$4,683
	50	KITTERY	0	$0	$0	5	$13,248	$2,650
	51	YORK	0	$0	$0	67	$728,667	$10,876
	52	WELLS	0	$0	$0	163	$968,974	$5,945
	53	OGUNQUIT	0	$0	$0	12	$314,691	$26,224
	54	KENNEBUNK	0	$0	$0	73	$908,290	$12,442
REGION VII	55	KENNEBUNKPORT	0	$0	$0	36	$686,087	$19,058
	56	BIDDEFORD	0	$0	$0	60	$237,044	$3,951
	57	SACO	0	$0	$0	41	$373,407	$9,107
	58	OLD ORCHARD BEACH	0	$0	$0	20	$73,983	$3,699
	59	SCARBOROUGH	0	$0	$0	13	$42,761	$3,289
	60	CAPE ELIZABETH	0	$0	$0	9	$39,753	$4,417
	61	PORTLAND	0	$0	$0	2	$1,635	$818

Blizzard of 1978 and to develop trends with offshore wave and water level conditions as described in Section "VI. Analysis and Comparison of Wave and Water Level Climates and Coastal Damages".

Based on the information provided by FEMA and FIA, the total monetary amount paid on direct and WYO claims and funds disbursed to municipalities was greater for the Halloween Storm ($93,788,200) than for the Blizzard of 1978 ($63,434,900). The total payments made on a regional basis to both municipalities and for direct/WYO claims are listed in Table 10.

TABLE 10

SUMMARY OF REGIONAL FUNDING

	Direct & WYO Claims		Funding To Municipalities	
Region	1978	1991	1978	1991
I	$2,500	$4,785,100	$0	$150,300
II	$168,100	$1,839,000	$257,700	$850,500
III	$162,100	$2,731,200	$384,700	$138,200
IV	$22,404,800	$42,562,200	$18,504,500	$4,268,600
V	$10,476,800	$18,355,000	$6,602,600	$3,051,600
VI	$2,515,300	$10,573,900	$1,851,900	$2,959,500
VII	$0	$1,454,700	$103,900	$68,400
TOTAL	$35,729,600	$82,301,100	$27,705,300	$11,487,100

The number of flood insurance policies issued under the NFIP probably increased between 1978 and 1991. Any disparity in dollar figures between the Blizzard and the Halloween Storm is not only due to differences in the wave and water level climates, but also a greater number of insurance policies resulting in a larger number of claims and payments. This may be true throughout the study area. This may be a significant factor for large differences exhibited in Table 10 for the Direct and WYO claims data between the two storms. Another reason for differences may be either the implementation or removal of shore protection structures between 1978 and 1991. However, any further analysis of damages requires an in-depth review of insurance claims and number of policies issued within a particular town, possible changes in local shore protection and land usage, and changes in coastal geomorphology such as the loss of a barrier beach (e.g., Chatham). Differences in funding amounts are also due to differences in the severity of the storms experienced in each region. A comparison of wave and water level climate for each storm and the most likely parameters (wave height, period, etc.) contributing to the damages, erosion, and flooding are outlined in Section VI, part h, "Wave and Water Level Factors Contributing To Economic Losses".

Introduction

Numerical modeling is applied as an interpolation tool to provide information in space and time where it is lacking. In-situ wave and water level measurements (e.g., NOAA wave buoys) provide needed information at specific sites. However, there is insufficient in-situ data of sea conditions along the New England coast to draw comparisons to or make judgements from. Therefore, in order to obtain a comparative basis for both storm events, it was necessary to use wave and water level hindcasting techniques. Two computer models were used to develop wave and water level hindcasts for the Blizzard of 1978 and the Halloween Storm of 1991. The first was Wave Information Studies (WIS) Wave Model (WISWAVE), Version 2.0. This model was used to develop wave characteristics for the two storms along the east facing New England shoreline. The model has also been used to develop a 20 year wave hindcast from 1956 to 1975 for the Atlantic seaboard from Puerto Rico to Canada. This hindcast is more thoroughly described in Hindcast Wave Information for the US Atlantic Coast, WIS Report No. 30, March, 1993. The water level hindcast used SURGE II which is a program for calculating storm surge and tide levels in a bay, estuary, or open coast. This model includes provisions allowing for the overtopping of barriers and, hence, flooding of normally dry areas. However, this feature was not included as part of this effort. Therefore, the model simulates the non-flooding water level due to wind induced surge at the coast.

The results of the hindcast and a discussion of the modeling procedure are contained in Appendix D - Wave and Water Level Hindcast which contains the report "Wind Wave and Water Level Hindcast Results for the Blizzard of 1978 and the Halloween Storm of 1991 for Coastal New England, Final Report - 1993". All times shown in Appendix D are in Universal Time Coordinates (UTC). (Subtract 5 hours from UTC to obtain Eastern Standard Time (EST).)

The model output has been exhibited at thirteen specific locations selected from the seventy-three nearshore stations where information was generated. Further information at these other sites may be obtained by contacting the U.S. Army Corps of Engineers, New England Division. Table 11 is a listing of the thirteen stations and their locations. These thirteen stations were chosen to include the study area boundaries, proximity to wave measurement buoys, and areas known to have experienced severe coastal damages which could be representative of damages throughout the study area.

The wave model WISWAVE 2.0 is described first, then the water level model SURGE II.

TABLE 11

HINDCAST STATION LOCATIONS

Station Number	Region	Location	Lat. Deg.	Lat. Min.	Long. Deg.	Long. Min.
72	VII	Buoy 44007	43	30	70	05
13	VII	Saco Bay	43	30	70	20
18	VI	Wells	43	15	70	30
25	VI	Hampton Beach	42	55	70	45
30	VI	Rockport	42	40	70	35
31	V	Eastern Point (Gloucester)	42	35	70	35
73	V	Massachusetts Bay Disposal Site (MBDS)	42	25	70	30
37	IV	Hull	42	20	70	50
38	V	Buoy 44013	42	20	70	45
40	IV	Scituate	42	15	70	40
48	III	Sandwich	41	50	70	25
66	II	Chatham	41	40	69	55
71	I	Sankaty Head Light	41	15	69	55

Wave Hindcast

The application of WISWAVE began with a definition of what was required from the model and why it was being used. The model can be used over a range of applications which includes hindcasting wave information on an oceanic scale for a short-term simulation of storm events such as the Halloween Storm. Waves arriving at the coast may have been generated by storms hundreds or even thousands of miles away. If the model coverage does not extend to these generation areas, this wave energy will not be represented. Thus, the first step was to define the boundaries of the region to be modeled. Once these boundaries were established, a grid of latitude and longitude lines were overlaid to define the points at which calculations were made. Because the model was required to cover a large area, a "nested" grid approach was used. This approach meant using smaller grids superimposed within the larger grids. This enabled a finer resolution of grid points to be established near the shoreline using five nautical mile intervals.

A time step parameter must was also established. The time step should generally be as large as possible without exceeding the time it takes for the fastest travelling wave energy to cross one grid cell. A common symptom of choosing too large a time step is excessive growth of wave energy resulting in unrealistic wave heights. The time step changes in a nested grid application since the grid spacing is reduced for the same climate of waves.

The outer grid boundaries in the ocean were chosen to realistically represent the fetch length to the region of interest, such as the shoreline. The model's output consists of a two-dimensional (frequency by direction) wave spectrum at every time step and grid point during the simulation. The model does not account for the effects of currents on wave propagation. The grid and modeling methodology are described more fully in Appendix D - Wave & Water Level Hindcast.

Various wave parameters for the Halloween Storm were evaluated for accuracy at four NOAA data buoys located within the study area. These include 44007, 44008, 44011, and 44013. Wave height, wave period (peak and mean), wave direction, and wind direction and speed are discussed below for each of the four stations. It should be noted that according to WIS Report No. 30, personnel at the National Data Buoy Center (NDBC) believe recorded wave heights from Buoy 44013 in Massachusetts Bay "underestimate actual conditions based on observations from local people in the region."

Overall model results for the hindcast wave heights were in general agreement with recorded wave heights from wave gages along the New England coast. However, due to model limitations, hindcast peak wave periods were lower than recorded peak periods by as much as approximately 6 seconds at NOAA data buoy 44011. The wave hindcast developed a spectrum which shows the distribution of wave energy as a function of wave frequency. This spectrum may contain two peaks, one associated with sea conditions and one with swell conditions. Sea conditions are those waves caused by locally generated winds. They usually contain steeper waves with shorter periods and lengths. The water surface also appears much more disturbed. Swell waves are wind generated waves which have traveled out of their generating area and usually exhibit a longer period.

The difference in peak periods associated with the energy density of sea and swell can introduce large fluctuations in the determination of peak periods. It is possible that the peak periods developed through the hindcast methods are those associated with locally generated seas (lower period), not the swell. In-situ buoy measurements may have measured periods which were associated with swell conditions. This is the primary cause of differences between the hindcast and in-situ peak period measurements. A more detailed evaluation of peak periods to determine how the energy is distributed in different frequency bands can be made, but are not within the scope of this study.

The differences between modeled and measured peak periods is more fully explained within the Coastal Engineering Research Center's report in Appendix D. ("Wind Wave and Water Level Hindcast Results for the Blizzard of 1978 and the Halloween Storm of 1991 for Coastal New England, Final Report - June 1993"). However, of greater importance is the fact that since both the Blizzard of 1978 and the Halloween Storm were modeled using the same methodology, the peak periods associated with the two storms are comparable even though they may not necessarily be representative of actual swell periods. Therefore, it is advisable that sound engineering judgement be used regarding the use of peak periods based on the hindcast wave climate data contained within this report.

Water Level Hindcast

Methods of determining storm surge due to water motion and responses to atmospheric stresses are equally valid for hurricanes and extratropical storms, but the framework of an extratropical storm is not as simple. The variability of wind fields causes a difficulty in deriving standard wind fields for storms other than hurricanes. Therefore, water levels were verified by comparing theoretical system response and computed water levels with those observed during the actual storm. The hindcast water levels are considered accurate within 1.64' (0.5 m) and are the best obtainable results within the scope of this study. The modeling methodology used in this study is more fully discussed in Appendix D - Wave & Water Level Hindcast.

VI. ANALYSIS & COMPARISON OF WAVE AND WATER LEVEL CLIMATES AND COASTAL DAMAGES

Introduction

This study is not an all inclusive accounting or assessment of the damages associated with the Blizzard or the Halloween Storm, but an attempt to develop correlations in trends between wave and water level characteristics and damages for the two storms which occurred in coastal communities from Nantucket, Massachusetts to Portland, Maine. This analysis of hindcast wave and water level climates and associated coastal damages was accomplished on a gross regional scale. Further evaluation of damages and offshore conditions is required for a more refined analysis at specific locations. The information generated by the hindcasting method for the two storms and the data collected on damages was used to evaluate differences in particular coastal parameters throughout the study region in order to identify trends between the wave and water level climate and coastal damages.

The general public's perception of the severity of the Blizzard of 1978 and the Halloween Storm are that both were "100-year" or comparable events. Although both were extremely devastating to the New England coastline and both resulted in millions of dollars of damage, these storms exhibited different characteristics which were responsible for the damages. The "100-year" label for the Blizzard is based on the maximum stillwater tide level. The Halloween Storm's maximum stillwater tide level had a frequency of only about 17 years. Other coastal processes and factors are involved when determining the severity of an event, and labeling a particular storm as a "100-year" event is misleading to both the public and emergency management agencies. Storms may cause severe damages similar to the Blizzard of 1978, but may not exhibit similar coastal characteristics such as stillwater level, wave height, and storm surge. Other factors to consider include the duration and the time of occurrence of the storm in relation to the normal or predicted tide cycle.

Regional Analysis

The combined effects of various storm parameters such as duration, wave direction, water levels, wave heights, and wave period all contributed to the severe and adverse conditions experienced along the New England shoreline for both the Blizzard of 1978 and the Halloween Storm of 1991. Various parameters have been evaluated to assist in developing correlations and trends with damages experienced along the shoreline. The two events also exhibited extremely different meteorological characteristics. The Blizzard was a major winter snowfall event throughout the New England area which contributed to damages and compounded hazardous conditions. However, the Halloween Storm was primarily a coastal event accompanied by heavy rain and high winds, especially in Massachusetts. According to the Natural Disaster Survey Report published by NOAA, the rapid westward motion and the location of the Halloween Storm before it turned in a southwest direction "contributed greatly to the coastal flooding and subsequent wave damage along the New England coast".

a. <u>Wave Period</u>

According to members of the Coastal Engineering Research Center (CERC) damage assessment team which arrived following the Halloween Storm, "the landward transport and accretion observed at various sites is in contrast to sediment transport patterns usually associated with winter storms. Interpretation of data indicates that this is likely due to the unusually long period waves which characterized this storm. Short period waves typically break in the surf zones, thus expending much of their energy. Waves of longer periods can move further landward before breaking. The net effect is that significantly more energy and seawater volume is driven into the nearshore. This is manifested by increased wave runup and higher water levels in the nearshore zone as well as shoreward transport of materials in the nearshore/surf zones."

The wave periods associated with the Halloween Storm were, in some cases, in excess of 20 seconds as measured at various NOAA wave buoys. However, due to hindcast model limitations, this excessive wave period was not exhibited within the model's output. This is because the peak period exhibited by the model's output is associated with that portion of the wave spectrum exhibiting the largest spectral energy density which is the result of locally generated seas, not swells. Therefore, the peak period of the hindcast model may not be representative of the large, long period swells which were characteristic of the Halloween Storm. This observation is based on direct comparison of observed and calculated peak periods for the same location. Because there are no in-situ wave measurements available for the Blizzard of 1978, hindcast results for the Blizzard are interpreted as being as accurate as those obtained for the Halloween Storm hindcast. Therefore, based on the difficulties in modeling wave periods for the Halloween Storm, the peak periods for the Blizzard may also not be accurately represented. Further analysis is required to disassociate the sea and swell peak periods from within the wave spectrum for both storm events.

Figures 15 and 16 represent the actual and hindcast peak wave period for two stations corresponding to NOAA wave data buoys near Portland (44007) and Boston (44013). The hindcast wave period is indicative of the highest period associated with the highest energy density within the modeled wave spectrum. These hindcast periods may not necessarily be associated with the longer period swell waves, but instead are associated with local sea conditions. Peak wave periods such as those which occurred during the Halloween storm are mostly associated with swell wave conditions which may not be reflected in the hindcast results. This is a reason why hindcast peak wave periods do not correlate with in-situ measurements at wave buoys.

In-situ peak wave periods for the Halloween storm were between 18 and 22 seconds as measured by four NOAA buoys (see Appendix D - Figure 1). Hindcast peak wave periods at these same locations were between 14 and 16 seconds, or about 4 to 6 seconds less than in-situ measurements. There were no in-situ wave measurements available for the Blizzard of 1978. It is recommended that sound engineering judgement be used when using the hindcast wave period data for determining site specific conditions.

The hindcast model covered a 100 hour duration for both storm events. The development, peak and decay portions of both events occurred during approximately the same time frames of the 100 hour modeled duration. For example, comparisons in the development of either storm can be made at about hour 30 of the model duration. The peak of either storm can be represented during the 60th hour and the decay during the 90th hour.

Development (30th Hour): The peak wave periods during the development stages of the Blizzard of 1978 (30th hour) were relatively uniform throughout the study area, ranging from 7 to 8 seconds. Peak wave periods during the development stages of the Halloween Storm showed much more variability ranging from 6 to 13 seconds throughout the study area. Peak periods of 13 seconds were observed from Wells to Portland, Maine with peak periods of about 8 to 9 seconds for the remainder of the study area. The largest difference in peak periods between the two storms was observed at the Massachusetts Bay Disposal Site (Station #73) and Nantucket (Station #71). At Station #73, the peak period during the development of the Halloween Storm was 6 seconds, or 2 seconds less than during the Blizzard of 1978. At Station #71, the peak period was 10 seconds, or 2 seconds more than that observed during the Blizzard of 1978.

Peak (60th Hour): The peak wave periods experienced at this time of the Halloween Storm ranged from 12 to 16 seconds. In contrast, peak periods during this time for the Blizzard of 1978 ranged from 11 to 13 seconds. During the peak of both events (60th hour), peak periods were up to 5 seconds longer during the Halloween Storm for the New Hampshire and Maine areas. The area from Buoy 44013 in Massachusetts Bay to Rockport, Massachusetts exhibited nearly the same peak wave periods for both storms and the Cape Cod and Nantucket areas experienced peak periods about 2 seconds longer for the Halloween Storm.

Decay (90th Hour): In general, during the decay stages of both storms (90th hour), peak wave periods were about 2 to 4 seconds longer throughout the entire study area for the Blizzard of 1978 than for the Halloween Storm. There was much less variability in peak periods for both storms during the decay stage.

In summary, peak wave periods were more variable throughout the study area during the development and peak of the Halloween Storm than at any time during the Blizzard of 1978. The largest differences in peak periods were experienced in the northern portions of the study area (New Hampshire and Maine) during both the development and peak of the two storms. Peak periods for this area were 5 to 6 seconds longer during the development and peak of the Halloween Storm. Variations in peak period for the remainder of the study area were much less pronounced. The Halloween Storm exhibited hindcast peak periods up to 2 seconds longer for the rest of the study area.

b. <u>Wave Height</u>

Figures 17 and 18 are graphic representations of the development, peak, and decay of wave heights for the two storms throughout the study area. The times are listed in Universal Time Coordinates (UTC) and wave heights are given in meters in order to correspond with data in

Appendix D. These figures are meant only to show the spatial and temporal relationships of the wave heights. The hindcast wave heights are considered an accurate representation of actual conditions within 3.3' (1 m). Specific hourly hindcast wave height data pertaining to a particular location or station may be obtained from Appendix D.

Figure 17 shows a uniform development of wave heights up to the peak of the Blizzard of 1978. Peak wave heights are relatively uniform throughout the study region, with a decreased magnitude shown near the Sandwich station which is due primarily to the shadowing effect provided by the outer portions of Cape Cod. The intensity and development of peak wave heights within the study area occurred as the storm tracked northward towards Cape Cod and the islands. However, within the next 24 hours following its peak the storm had passed Cape Cod and was well east of Nova Scotia and south of Newfoundland.

Peak wave heights occurred at about 7:00 AM EST (12:00 PM UTC) on February 7 for stations located in Portland, Saco, Wells, and Hampton (Regions VI and VII). They averaged about 25.6' (7.8 m), or almost 6.6' (2 m) higher than peak wave heights experienced during the Halloween Storm. The storm at this time was located south of New England, closer than the Halloween Storm ever came.

Peak wave heights at stations located offshore of Rockport, and Eastern Point in Gloucester, Massachusetts (Regions V and VI) occurred at about 1:00 AM EST (6:00 PM UTC) and averaged about 27.6' (8.4 m), or almost 1.6' (0.5 m) higher than those exhibited during the Halloween Storm.

Those stations located within Massachusetts Bay and Cape Cod Bay (Regions III, IV and V) exhibited peak wave heights averaging 27.2' (8.3 m). These also occurred at close to the same time as peak wave heights in Maine (7:00 AM EST). These peak wave heights were also slightly larger than those which occurred during the Halloween Storm. A peak wave height of 18.4' (5.6 m) occurred at Sandwich (Region II) at approximately 3:00 AM EST (8:00 UTC) on February 8, almost a full day after peak wave heights occurred at other stations north of Chatham. At this time, the storm was well east of Nova Scotia. This wave height was about 11.5' (3.5 m) less than peak wave heights at this location for the Halloween Storm.

Peak wave heights of 26.2' (8 m) occurred off of Chatham and Nantucket (Regions I & II) at about 2:00 AM EST (7:00 AM UTC) on February 7, about five hours prior to peak wave heights occurring at all other stations except Sandwich. This is consistent with the storm's track which was located south of Long Island. Wave heights off of Chatham and Nantucket had diminished to 24.6' (7.5 m) by the time peak wave heights occurred at the other stations. The peak wave height of 26.2' (8 m) was almost 11.5' (3.5 m) less than that experienced during the Halloween Storm.

Figure 18 shows a more complex development of wave conditions to the peak of the Halloween storm. Peak wave heights are not as uniformly distributed throughout the study area as those exhibited during the Blizzard of 1978. However, the magnitude and duration of extreme wave heights on the east facing shores of Cape Cod and Nantucket (Regions I and II) are greater than those exhibited during the Blizzard of 1978. The relationship between wave heights and duration is more fully discussed later under the "Storm Power" section. Peak wave heights occurred at differing times throughout the study area as the storm moved closer to the New England region.

In the northern portion of the study area (Portland, Saco, Wells - Regions VI and VII), peak wave heights occurred at approximately 2:00 AM EST (7:00 AM UTC) on October 31. The storm was located directly south of Cape Cod and peak wave heights averaged about 18.4' (5.6 m). At stations in New Hampshire and northern Massachusetts (Hampton, Rockport, Eastern Point - Regions V and VI) peak wave heights occurred three hours before those in Maine or at about 11:00 PM EST, October 30 (4:00 AM UTC, October 31). They averaged 25.6' (7.8 m) in this area.

Further south within Massachusetts Bay and the shoreline south of Boston (Regions IV and V), peak wave heights occurred at about the same time as those in Maine. However, they averaged about 25.9' (7.9 m), or over 6.6' (2 m) higher than those exhibited at stations in Maine. The peak wave height at Sandwich (Region III) occurred at about 10:00 PM EST, October 30 (3:00 AM UTC, October 31) and diminished rapidly just as stations further north such as Hull and Scituate were experiencing peak wave heights.

Peak wave heights between 33.8' (10.3 m) and 37.4' (11.4 m) at Chatham (Region II) and Nantucket (Region I), respectively occurred at about 7:00 PM EST, October 30 (12:00 AM UTC, October 31). This was 7 hours prior to peak wave heights occurring at the stations in Maine and 4 hours prior to those located in Massachusetts Bay. These wave heights were between 11.5' (3.5 m) to 16.4' (5 m) higher than those exhibited during the Blizzard.

Table 12 above illustrates the differences in peak wave heights throughout the study area. In summary, peak wave heights were relatively uniform throughout the study area during the Blizzard of 1978. Peak wave heights were more varied throughout the study area and more intense near Cape Cod and Nantucket (Regions I and II) for the Halloween Storm. Wave heights and their duration in the southern parts of the study area during the Halloween Storm were a significant factor contributing to damages and erosion. The opposite is true of the wave heights during the Blizzard of 1978. For that storm, the waves were a contributing factor to shoreline damages in the northern parts of the study area, such as in Maine.

TABLE 12

PEAK WAVE HEIGHTS

Station Number	Region	Location	Peak Wave Heights (ft) 1978	1991
72	VII	Buoy 44007	27.6	20.7
13	VII	Saco Bay	24.0	18.7
18	VI	Wells	24.6	19.7
25	VI	Hampton Beach	26.2	22.6
30	VI	Rockport	27.2	26.6
31	V	Eastern Point	27.6	27.6
73	V	MBDS	26.9	28.2
37	IV	Hull	27.2	24.3
38	V	Buoy 44013	26.9	25.9
40	IV	Scituate	27.2	27.6
48	III	Sandwich	18.4	29.2
66	II	Chatham	26.2	33.8
71	I	Sankaty	26.2	37.4

The wave climate modeling was accomplished at 5 nautical mile spacings from Nantucket, Massachusetts to Portland, Maine and the data can be used for further evaluation. A total of 73 nearshore stations are located within the study area. Hindcast wave and water level data is available for each of these stations for use in determining the onshore wave conditions associated with extreme storm events. This information may be obtained by contacting the Army Corps of Engineers, New England Division. The latitude and longitude of the 73 stations closest to shore are listed in Appendix D.

c. Storm Power

The following discussion of storm power is based on the article; "An Intensity Scale for Atlantic Coast Northeast Storms", by Robert Dolan and Robert E. Davis. This originally appeared in the Journal of Coastal Research, Vol. 8, No. 4, 1992. Storm power is defined by the wave height and the storm's duration, which is defined by the length of time a wave height of 4.9' (1.5 m) is exceeded. Dolan and Davis have established a classification system for extratropical storms for the middle Atlantic coast. It should be noted that although Dolan and Davis feel the criteria used to classify the storms into one of the five classes described below is universally applicable, the distribution of storms in each class may vary between the Mid-Atlantic and New England coasts. However, this classification system is still a useful tool for comparing the relative strength of coastal storms in other areas as well, such as New England. Therefore, this classification system has been used to compare the

strength and intensity of the Blizzard of 1978 with the Halloween Storm of 1991, and to provide an approximation of the return period of these storms. The Dolan-Davis classification system will also be useful for comparing any future events with these two storms.

The classification variable is an index of storm "power" which is the storm's duration multiplied by the square of the maximum significant wave height. (Units are meters squared - hour.) The system was based on wave hindcasts of over 1,300 storms over a 42 year period which were grouped into five classes. The five classes are:

CLASS I	-	Weak:	Power $\leq$ 771 ($ft^2hr.$)
CLASS II	-	Moderate:	771 < Power $\leq$ 1,760
CLASS III	-	Significant:	1,760 < Power $\leq$ 10,000
CLASS IV	-	Severe:	10,000 < Power $\leq$ 25,000
CLASS V	-	Extreme:	Power > 25,000

As previously discussed, peak wave periods may not have been accurately represented within this study's hindcasting methodology of the wave climate. This has been previously discussed under section "V. Hindcast Model". Furthermore, this classification system is independent of the predicted tide cycle. Therefore, utilizing the Dolan-Davis storm classification system is especially desirable in this effort because it does not rely on wave periods as a classification parameter. Peak wave height and storm duration are the parameters used to classify the storm intensity. The duration is dependent on the wave height, and is defined as the time period when waves are 4.9' (1.5 m) or higher. Therefore, because the hindcast wave heights are relatively accurate, the storm power classification system is a useful parameter for comparing and describing the two storm's effects on the New England shoreline.

Based on this classification system, and using the results of the hindcast modeling effort, it was possible to determine the storm power of both events. The Table 13 shows the peak storm power for each region. The peak storm power is based on peak wave heights exhibited at each station.

The information in Table 13 is based solely on the results of the WISWAVE 2.0 hindcast model, and not actual measured data from NOAA wave data buoys. In some instances, the duration of wave heights over 4.9' (1.5 m) had to be extrapolated since the hindcast data did not cover the decay portion of the storm's wave climate past the 4.9' (1.5 m) wave height. The storm power is a good representation of the contrast in the severity between the two storms on a regional scale. The storm power throughout the study area for both storms is classified as Class V.

TABLE 13

PEAK STORM POWER

Station Number	Region	Location	Storm Power ($ft^2hr.$) 1978	1991
72	VII	Buoy 44007	52,718	34,737
13	VII	Saco Bay	41,521	25,315
18	VI	Wells	48,030	29,202
25	VI	Hampton Beach	58,746	38,111
30	VI	Rockport	55,881	56,022
31	V	Eastern Point	57,236	59,495
73	V	MBDS	51,672	63,152
37	IV	Hull	55,881	46,173
38	V	Buoy 44013	51,672	51,957
40	IV	Scituate	54,411	61,002
48	III	Sandwich	26,777	63,407
66	II	Chatham	51,915	122,292
71	I	Sankaty	48,499	145,646

Dolan and Davis also utilized their storm power classification system for the Halloween Storm. They used wave hindcast data at Cape Hatteras, North Carolina to obtain a storm power over 139,650 ft^2hr.. Comparing this result to their climatological data base of 1,347 Atlantic extratropical storms over a 42 year period revealed that the Halloween Storm of 1991 was the strongest storm on record. Their findings also compare well with the storm's power off Cape Cod and Nantucket.

Figures 19 and 20 are graphic representations of the variations in peak storm power throughout the study area for both storms. (Both figures are in metric in order to match wave data contained in Appendix D.) These figures are meant only to portray the variations in storm power throughout the study area. The peak storm power is up to three times greater in the southern portion (Nantucket, and Chatham) of the study area for the Halloween event than for the Blizzard of 1978. This is primarily due to a combination of peak wave heights over 9.8' (3.0 m) higher and duration about 30 hours longer for the Halloween Storm. Overall the Halloween Storm was more intense near Cape Cod and Nantucket. The Blizzard of 1978 was more intense in the northern portions of the study area from Hampton to Portland, however, the difference in storm power magnitude between the two events was not as pronounced in New Hampshire and Maine as it was on Cape Cod. The greater storm power in New Hampshire and Maine exhibited during the Blizzard is due mostly to wave heights being almost 6.6' (2 m) higher than peak wave heights experienced during the Halloween Storm. A review of the duration of wave heights exceeding 4.9' (1.5 m) shows that the duration was greater during the Halloween Storm except at Hampton

and Wells. However, even these differences are minor (3 to 12 hours) when compared to differences in duration near Cape Cod and Nantucket where it was over 30 hours longer than during the Blizzard of 1978. This is a primary reason for the extreme erosion and damages observed at locations such as Nantucket following the 1991 storm.

d. Wave Direction

The direction of wave propagation in relation to the shoreline can have a direct result on erosion and damages along a shoreline. However, the wave directions produced by the hindcast modeling process are not refined enough to determine their effect on specific portions of the coastline. Further analysis is required through the use of wave refraction and propagation techniques. Comparisons of wave concentration and energy with damages exhibited along the coast is best accomplished by utilizing further wave refraction and propagation techniques such as the Regional Coastal Processes Wave Propagation (RCPWAVE) model. Therefore, only general comparisons between the 1978 and 1991 events can be made.

As described in Appendix D, the hindcast model for both storms covered a 100 hour duration for both storm events. The development, peak and decay portions of both events occurred during approximately the same time frames of the 100 hour modeled duration. For example, comparisons in the development of either storm can be made at about hour 30 of the model duration. The peak of either storm can be represented during the 60th hour and the decay during the 90th hour. The following analysis of wave direction is based on comparisons made during these specific time periods.

Comparisons of wave direction during the development, peak and decay of the two storm events was accomplished at Stations: 72 (Buoy 44007 - Region VII), 25 (Hampton Beach - Region VI), 38 (Buoy 44013 - Region V), 48 (Sandwich - Region III), and 71 (Sankaty Head Light - Region I).

The most significant difference in wave direction between the two storm events occurred at Station 71 off Nantucket. The wave directions during the development and decay portions of both storms were similar. However, during the peak of the storms, when the largest wave heights were impacting the shoreline, the wave direction was from an east-southeast direction in 1978 and from the northeast during the 1991 event. Without further analysis using wave refraction and propagation techniques, it is not possible to determine whether this difference in direction is a significant factor contributing to erosion and storm damage at onshore locations near Nantucket.

Wave directions for both storm events were similar for other locations, coming primarily from the northeast to easterly direction throughout the course of either event. This is despite the fact that the storms approached New England from opposite directions. Therefore, due to the similarity in wave directions for both storm events, it is doubtful that this parameter contributed greatly to major differences exhibited in onshore damages and erosion between the two storm events, except for possibly Nantucket and Cape Cod. However, local differences in wave direction were not examined and may have contributed to differences in damages at specific sites.

e. <u>Water Levels</u>

The water level associated with each storm was also hindcast at each of the stations. As previously discussed in Section "IV. Storm Impacts", the Halloween storm's occurrence during a period of normal astronomical tides spared many coastal areas from even greater damage.

Although the high portion of the tide cycle was greater in 1978, the storm surge was greater during the 1991 event. However, the maximum observed water levels were still greater during the Blizzard of 1978 at both Boston and Portland. The maximum observed water level associated with the Blizzard of 1978 at Boston was approximately 10.3' NGVD (3.1 m). It was 9.4' NGVD (2.9 m) for the Halloween Storm. At Portland, the maximum observed water levels were 9.6' NGVD (3.0 m) and 8.2' NGVD (2.4 m) for the Blizzard and the Halloween Storm, respectively. The differences in water levels are due in part to the predicted tide cycles during which the two storms occurred. The highest predicted tide levels during February 6 through 8, 1978 were about 6.8' NGVD (2.1 m) at Boston and Portland, respectively. The highest predicted tide levels during late October and early November, 1991 were about 5.0' NGVD (1.5 m) at Boston and Portland, respectively.

There is little variation in hindcast water levels between most stations, except for those located off of Chatham and Nantucket. The magnitude of the range in water levels between high and low is not as pronounced at these stations, however, the general pattern of high and low water levels is similar to other stations in Massachusetts Bay and further north.

A comparison of the water levels between the hindcast (Station #38 - Buoy 44013) and measured values (Boston - NOS tide gauge) was also accomplished. These two locations are approximately 10 nautical miles apart which may account for some discrepancy between measured and hindcast water levels. It was found that hindcast water levels for the Blizzard lag the measured data by about 3 hours and the hindcast tide levels are 3.3' to 4.9' (1.0 to 1.5 m) greater during the development of the storm to the peak wave heights. At the peak of the Blizzard, there is an over 6.6' (2.0 m) difference in hindcast and measured water levels, due primarily to the 3 hour time lag. However, if this time lag were arbitrarily corrected by setting the hindcast time frame ahead 3 hours, the hindcast water level data matches the measured water level data very well. For example, during the peak of the storm the hindcast water level would match the measured data to within 0.7' (0.2 m).

For 1991, peak hindcast water levels were about 3.3' (1.0 m) higher during the development of the storm. The variation between high and low water levels was also more pronounced in the hindcast data than the measured data. The time lag between the hindcast and measured data was not as pronounced for the Halloween Storm as it was for the Blizzard and the high water levels agreed to within 0.7' to 1.3' (0.2 to 0.4 m) during the peak of the Halloween Storm.

Table 14 illustrates peak water level differences between the two storms and among the thirteen stations. In general, based on the hindcast water levels, those associated with the Blizzard of 1978 were about 2' (0.6 m) higher than water levels experienced during the Halloween Storm. However, this is not true at the stations located in the southern portion of the study area. The water level at the Sandwich station was almost 3' (0.9 m) higher during the Blizzard than the water level at this same location during the Halloween Storm. The water level difference at Chatham was negligible, however, at Nantucket, the peak water level was over 1.0' (0.3 m) greater during the Halloween Storm.

TABLE 14

PEAK WATER LEVELS

Station Number	Region	Location	Peak Water Levels NGVD (ft) 1978	1991
72	VII	Buoy 44007	9.2	7.9
13	VII	Saco Bay	9.5	7.9
18	VI	Wells	9.8	8.9
25	VI	Hampton Beach	11.8	9.8
30	VI	Rockport	11.5	9.5
31	V	Eastern Point	11.5	9.8
73	V	MBDS	12.1	9.8
37	IV	Hull	12.8	10.8
38	V	Buoy 44013	12.8	10.5
40	IV	Scituate	12.5	10.5
48	III	Sandwich	14.1	11.2
66	II	Chatham	8.5	8.2
71	I	Sankaty	8.9	9.8

As with waves, the duration of high water levels due to storm surge can have a significant effect on flooding, damages and erosion. Duration is based on the time the storm surge exceeded 1.0' (0.3 m). At Boston, the duration for the Blizzard was about 45 hours. However, for the Halloween Storm it was almost 90 hours. At Portland, it was 32 and 46 hours, respectively, for the Blizzard and Halloween storms. This means that the New England shoreline, in general, was exposed to higher than normal water levels (storm surge > 1.0') for a longer period of time during the Halloween Storm than during the Blizzard of 1978.

One of the major differences in water levels between the two storm events is due to the normal tide cycle during which each storm occurred. For example, if the Halloween storm had occurred five days earlier, the stillwater level at Boston would have been about 1.5' (0.5 m) higher.

This would have surpassed the 1978 maximum observed water level at Boston by almost 0.5' (0.2 m). This water level, in conjunction with large long period waves, could have led to extreme coastal damages throughout the study area. These damages would have likely exceeded the highest damages recorded from either the Blizzard or the Halloween events.

f. Return Period of Halloween Storm Event

Various return periods associated with the Halloween Storm at Boston, Massachusetts (Buoy 44013), and Portland, Maine (Buoy 44007) are shown in Table 15. These include maximum stillwater level, maximum surge, and wave heights. This table gives a general indication of the potential severity of both storm events and of the need to accurately characterize the event based on return periods. For example, characterizing the Halloween Storm as a "17-year" event at Boston compared to the Blizzard of 1978 (a "100-year" event) is not necessarily an accurate representation. Based on this characterization, one could conclude that the Blizzard's intensity or potential for damage was far greater. However, as previously discussed, the storm power of the Halloween event was similar to the storm power associated with the Blizzard of 1978 at this location. The storm surge for the Halloween event was also greater than that observed during the Blizzard. Therefore, when characterizing a particular storm event, various parameters should be investigated to obtain an accurate understanding of the severity of the storm before labeling the event with a frequency such as the "100-year" storm.

TABLE 15

RETURN PERIODS AT BOSTON, MASSACHUSETTS AND PORTLAND, MAINE

	RETURN PERIOD (Years)			
	Blizzard of 1978		Halloween Storm of 1991	
	Bost.	Port.	Bost.	Port.
Maximum Stillwater Tide Levels	100	133	17	4
Maximum Storm Surge	35	4	90	10
Wave Heights	10	30	15	4
Storm Power	60	60	60	35

The return periods for the wave heights are based on results obtained from hindcast wave information for the 20 year period from 1956 to 1975. The return periods were obtained from Appendix B of the "Hindcast Wave Information for the US Atlantic Coast", WIS Report No. 30, March, 1993. Wave return periods at various stations close to those used in the 20 year hindcast are provided in Table 16. Return periods for the storm power are estimated from "The 'All Hallows Eve' Coastal Storm - October 1991", by Robert Dolan and Robert E. Davis in the Journal of Coastal Research, Fall 1992.

TABLE 16

WAVE HEIGHT RETURN PERIODS
FOR VARIOUS LOCATIONS

Location/Station #	Approximate Return Period (Years) 1978	1991
Nantucket/ #71	50	> 50
Scituate/ #40	40	40
Mass. Bay/ #73	10	15
Eastern Point/ #31	12	12
Rockport/ #30	16	13
Saco/ #13	50	8
Portland 44007/ #72	30	4

Based on the information contained in Table 16, it can be seen that the return periods associated with the Blizzard in the northern portion of the study area reflect a more severe wave climate than the Halloween Storm. However, the return period for Nantucket does not reflect the disparity of wave heights exhibited at this location between the two storms. Wave heights at this location were 26.2' (8.0 m) and 37.4' (11.4 m) for the Blizzard and Halloween storms, respectively. Furthermore, other wave characteristics such as wave period are not included. Larger period swell waves are capable of transferring their energy further landward, thereby possibly causing increased damages. This a good example of why return periods based on a single parameter should be used with caution when either describing a single storm event or comparing two storms.

g. Storm Track and Position

The location of the two storm events was a significant factor in determining the impacts of each storm. Furthermore, the presence and proximity of Hurricane Grace contributed to the intensity of the Halloween Storm. The rapid westward advance of the Halloween Storm and its proximity to the shoreline were contributing factors to the severity of damage and erosion within New England.

Whereas the Blizzard of 1978 followed a storm track common along the eastern seaboard, the Halloween Storm did not. The Blizzard developed and moved northeasterly along the east coast. However, the Halloween Storm approached New England from the east. It was influenced primarily by the large anticyclone (high pressure area) over northern New England and Canada and Hurricane Grace which contributed to the development and intensification of the original low pressure area. The development and track of the Halloween Storm was unique in that it did not follow the normal patterns associated with an extratropical storm.

The Halloween storm track provided the opportunity for a longer duration of larger waves and higher than normal water levels to impact the New England coast, particularly on Cape Cod and the area south of Boston. Figure 1a shows the track of the Blizzard of 1978 and the Halloween Storm. For example, while the Blizzard moved from south of Long Island to south of Nova Scotia in a 24 hour period which includes the peak of the storm, in a similar 24 hour period, the Halloween Storm moved and remained closer to New England. It is apparent that the storm track and its position had a significant effect on those areas within the southern portion of the study area, particularly Cape Cod and Nantucket. This is reflected in the peak wave heights and storm power experienced near Cape Cod (Chatham) and Nantucket.

h. <u>Wave & Water Level Factors Contributing to Economic Losses</u>

The following assessment is meant only to portray the likely causes or contributing factors to the damages attributed to either the Blizzard or Halloween Storm on a regional basis. Further evaluation of damages incurred from the two storms on a town or site-specific basis requires careful consideration of a number of factors. Some of these factors include possible land use changes and the use of protective structures and measures implemented between 1978 and 1991. Other factors influencing the severity and dollar amount of damages among towns include: length of shoreline, coastal topography (elevation) and geology, and erosion from other storm events occurring between 1978 and 1991. For example, damages in the town of Chatham from the Halloween Storm are most likely due to the breach of Nauset Beach which occurred in January 1987, but this must be verified with a more site-specific evaluation.

This study is limited to a regional evaluation of the damages based on information obtained from the Federal Emergency Management Agency and the Federal Insurance Administration.

The following is a discussion of the factors which most likely contributed to the damage, erosion and flooding within the study area for both the Blizzard and Halloween Storm. Damages occurring onshore were the result of a combination of high water levels, large wave heights, and the long duration for both storm events.

A review of wave heights and their duration indicates that they were probably a major cause of damages in the northern portion of the study area (Regions VI and VII) during the Blizzard of 1978. For example, there were no wave heights exceeding 7 meters from the Hampton station north to Portland during the Halloween Storm. However, wave heights over 23.0' (7 m) within this area averaged about 9 hours in duration for the Blizzard. Economic losses and damages occurring from the Halloween Storm in excess of those which occurred due to the Blizzard in the southern portions of the study area (Regions I and II) are most likely the result of large long period waves over a long duration and changes in the number of flood insurance policies issued between 1978 and 1991.

Peak wave periods recorded at NOAA data buoys were between 16 and 22 seconds for the Halloween Storm. This is a significant contributing factor because long period waves are capable of moving further landward before breaking and dissipating their energy, thereby causing flooding, damage, and erosion to areas not normally subjected to wave action. Hindcast wave periods associated with the Blizzard were about 4 to 6 seconds less and probably were not as significant a factor in contributing to the damages from that storm.

A major contributor to the damages and potential for damages was the occurrence of the storm in relation to the tide cycle. As previously discussed, had the Halloween Storm of 1991 occurred five days prior to October 30, coastal damages could have far exceeded those which had occurred in either 1978 or 1991. However, the occurrence of either event is independent of the tidal cycle and is coincidental with such aspects as a perigean tide when the moon's orbit is closest to the earth. This was the case with the Blizzard of 1978.

Excessive water levels and their duration are another contributing factor to the damages observed throughout the study area. The storm surge associated with the Halloween Storm was between 0.5' (0.2 m) and 0.7' (0.2 m) higher than the storm surge from the Blizzard. However, maximum stillwater levels (which includes storm surge) for the Blizzard were about 2.0' (0.6 m) higher throughout the study area. The duration of storm surge was greater for the Halloween Storm (90 hours) than for the Blizzard (45 hours). Therefore, while stillwater levels had a significant impact on the amount of flooding, damages, and erosion experienced during the Blizzard, the duration of higher than normal water levels during the Halloween Storm was a significant contributing factor. High water levels are capable of supporting large wave heights. Since the duration of higher than predicted water levels for the Halloween Storm was double that of the Blizzard of 1978, large, long period waves were capable of impacting the shoreline for a longer period of time. Therefore, the duration of higher than normal water levels was probably a major contributing factor to damages observed due to the Halloween Storm.

A summary of the hindcast wave and water level climate on a regional basis is given below and is related to economic losses based on private insurance claim data and funding provided by FEMA to municipalities.

Regions I & II

Peak wave heights were about 11.5' (3.5 m) higher and duration of wave heights over 4.9' (1.5 m) was about 30 hours longer for the Halloween Storm than for the Blizzard. Peak periods were up to 4 seconds longer than those experienced in the Blizzard of 1978. The storm power was also significantly greater for the Halloween Storm due to the larger wave heights and longer duration of these waves. Peak water levels were slightly over 1.0' (0.3 m) greater during the Halloween Storm off of Nantucket, however, they were about the same at Chatham. The differences in wave characteristics were the major contributing factor in the differences between damages, erosion, flooding, and to some extent economic losses experienced in these regions during the two storms. Wave direction during the peak of the events may have also played a role in contributing to the severity of erosion of east facing shores such as the Sankaty and Siasconset areas of Nantucket, however, this requires further investigation.

Region III

This region is located within Cape Cod Bay and the wave climate is influenced by the portion of Cape Cod extending north to Provincetown, Massachusetts. The hindcast model station representing this region is located off of Sandwich in Cape Cod Bay. The peak wave height was over 9.8' (3.0 m) higher during the Halloween Storm and the peak period was about the same for both storms. The storm power was almost 2.5 times greater for the Halloween Storm, which is reflected by the greater peak wave heights. However, peak water levels were estimated to be almost 3.0' (0.9 m) higher during the Blizzard of 1978. Therefore, it appears that the wave height was the primary contributing factor to damages from the Halloween Storm while the water level was the significant contributing factor from the Blizzard of 1978.

The disparity in the amount of economic losses from the two storms ($546,800 for the Blizzard versus $2,869,400 for the Halloween Storm) can be attributed to the excessive wave climate and other possible factors such as the number of insurance policies issued within this region between 1978 and 1991 and subsequently the number of claims made.

Regions IV, and V

Average peak wave heights were slightly larger for the Blizzard (27.2'(8.3 m)) than the Halloween Storm (26.7'(8.1 m)) for these regions. The storm power was also similar within the regions extending from Gloucester, Massachusetts south through Massachusetts Bay to Cape Cod Bay. Because peak wave heights and storm power were similar for both events, this is an indication that the duration of large wave heights was also similar for both events. Hindcast peak periods in these regions at the height of both storms were about 12 to 13 seconds. Wave direction during the development, peak, and decay for both storms was also similar for these regions.

Due to the similarities in wave heights, storm power, peak wave period, and wave direction for these regions, it is unlikely that these parameters were the major factors contributing to differences in economic losses observed between the two storms. These regions experienced over $9.9 million more in economic losses associated with the Halloween Storm. The most significant differences between the two storms is that the peak water levels were approximately 2.0' (0.6 m) higher for the Blizzard of 1978 and the duration of storm surge over 1.0' (0.3 m) was about 90 hours for the Halloween Storm versus only 45 hours for the Blizzard of 1978.

Therefore, despite higher stillwater levels during the Blizzard, it is likely that the differences in economic losses can be attributed to two items. First, the longer duration of higher than normal water levels associated with the Halloween Storm and secondly, factors such as the number of insurance policies issued and claims made in 1991 versus 1978.

Region VI and VII

Peak wave heights during the Blizzard of 1978 were up to 7.6' (2.3 m) higher, however, the overall duration of wave heights exceeding 4.9' (1.5 m) was greater during the Halloween Storm. The storm power was greater for the Blizzard of 1978 due to the larger peak wave heights experienced in these regions. Peak wave periods associated with these regions were up to 6 seconds longer during the Blizzard of 1978. Wave direction during the development, peak, and decay of both storms was similar for these regions. The peak water levels averaged 10.4' NGVD (34.1 m) during the Blizzard and 8.8' NGVD (28.9 m) during the Halloween Storm.

The duration of a storm surge greater than 1.0' (0.3 m) producing higher than normal water levels at Portland, Maine was about 14 hours more during the Halloween Storm than during the Blizzard of 1978.

It is apparent that the wave climate and water levels within these regions were more severe for the Blizzard of 1978 than the Halloween Storm. However, these regions experienced approximately $10.6 million more in economic losses as a result of the Halloween Storm. Of that $10.6 million difference in economic losses, about $9.5 million can be attributed to direct and WYO claims. Therefore, it appears that the greater economic losses resulting from the Halloween Storm may be due to changes in the number of insurance policies and subsequent claims made as a result of the 1991 storm event and not necessarily differences in the wave and water level climate.

i. <u>Comparison of Wave & Water Level Hindcast Results to the 100-Year Flood Boundary and Wave Envelope</u>

There has been concern that the existing 100-year flood boundaries identified in flood insurance studies accomplished by FEMA may not adequately address the flooding potential from events such as the Halloween Storm of 1991. Therefore, a brief review of the 100-year stillwater elevation and the associated wave characteristics used to develop the wave envelope for the flood insurance studies was

accomplished. Flood insurance studies for communities near the thirteen hindcast stations were used for the review.

Within the flood insurance studies conducted by FEMA, areas of the coast subjected to wave attack are referred to as coastal high hazard areas. Wave height analyses were performed in the flood insurance studies to determine nearshore wave parameters such as the breaking wave height, period, and corresponding wave crest elevations within these high hazard areas. Wave runup was also determined using the results of the nearshore wave height analyses. The results of the wave height and runup analyses were then combined to obtain a wave envelope elevation based on the 100-year storm surge for each coastal community.

Comparing the hindcast wave characteristics of the Halloween Storm with the wave climate information in the flood insurance studies reveals that in some cases the hindcast wave heights were higher than the significant wave heights developed in the flood insurance studies. Also, by using hindcast wave periods adjusted for the differences identified between hindcast and observed peak periods (4 to 6 seconds) for the Halloween Storm, it was found that the periods used within the flood insurance studies could be about 5 to 8 seconds shorter than those produced by the Halloween Storm.

The wave characteristics associated with the Halloween Storm frequently exceeded those used to develop the 100-year wave envelope in various communities. For example, the wave parameters used in the flood insurance study at Hampton, New Hampshire were a 30' (9.1 m) significant wave height with a 14 second period. However, the wave hindcast produced a 22.6' (6.9 m) wave with a possible wave period of 22 seconds, or 8 seconds longer than the period used in the flood insurance study. In the flood insurance study for Scituate, Massachusetts the wave envelope was developed using a significant wave height of 19' (5.8 m) with a period of 12.5 seconds. The offshore results of the wave hindcast revealed a 27.6' (8.4 m) wave with a possible wave period of 19 seconds. This example shows that for this location the hindcast wave height exceeded the flood insurance study wave height by almost 9' (2.7 m) and the hindcast period exceeded the flood insurance study period by 6.5 seconds. At Nantucket, the flood insurance study used a 19' (5.8 m) significant wave height with a 12.5 second period. The wave hindcast results showed a 37.4' (11.4 m) wave with a possible 20 second period. The hindcast results for Nantucket reflect a much more severe wave climate than was used within the flood insurance study.

The results of the Halloween Storm hindcast are for offshore points. These waves must first be propagated towards the shoreline taking into account refraction, diffraction, and shoaling in order to provide a better comparison with wave characteristics used to develop the wave envelope in the flood insurance studies. Furthermore, the differences in wave period noted above could be a significant factor in the reason why damages were more severe than expected in certain areas. Corps of Engineers damage assessment teams reported that observed sediment transport patterns and landward transport of materials were characteristic of unusually long

period waves. Based on this review, it appears that the wave climate associated with the Halloween Storm may not be accurately represented in the results of flood insurance studies.

A comparison of the hindcast water levels at various stations with stillwater elevations obtained from the flood insurance studies (for the closest municipality to that station) reveals that the hindcast water levels are consistently near or greater than the 100-year stillwater levels. However, this does not correspond with tide gage readings at Boston and Portland which indicated that the Halloween Storm was less than a 20-year event at both locations. As previously described, the hindcast water levels for the Halloween Storm do not include shoreline flooding of normally dry areas. It does not account for flooding caused by the combination of water levels and wave heights as the flood insurance studies do. Furthermore, the hindcast results are for particular points offshore, not at the shoreline as the flood insurance study results are. Therefore, hindcast water levels are inconclusive for comparing to the 100-year flood boundary unless a more detailed water level analysis of the Halloween Storm to obtain comparable results along the shoreline is accomplished.

Summary

Although the Halloween Storm's wave and water level characteristics were not within the 100-year frequency parameters established within various flood insurance studies, FEMA believes that revisions to the delineation of flood boundaries are not warranted. This is because FEMA uses wave parameters that statistically represent a 100-year tropical or extratropical storm event. A less frequent event such as the Halloween Storm can equal or exceed the inundation and damages associated with a 100-year event because it exhibits extreme characteristics such as long wave periods. Therefore, the 100-year flood boundaries and wave envelopes defined in the flood insurance studies are adequate representations of conditions likely to exist due to extratropical storms which exhibit typical 100-year water levels and wave characteristics. According to FEMA, various communities within the study area are also scheduled to have their flood insurance studies updated in 1995. These include Scituate, Duxbury, and Marshfield.

VII. CONCLUSIONS

The following conclusions are based on information and data gathered during the course of this study and an analysis of wave and water level conditions at various points within the study area. This analysis has shown which coastal parameters were most likely major contributing factors in particular areas to the damage, erosion, and flooding experienced within the study area of New England.

1. Throughout the course of this study and in meetings held with various state agencies from Maine, Massachusetts, and New Hampshire, the question of frequency, or return periods, was raised. However, as can be seen by the results of this study, a particular frequency cannot be associated with either storm. Frequencies or return periods are better associated with only certain aspects of a storm event, such as maximum stillwater level, storm surge, or wave height. Therefore, the frequency or return period of an event depends on the specific parameters which may be of particular importance to the reader.

Storms are often characterized by their maximum stillwater level frequency which does not account for severe wave conditions which may also exist. While many coastal structures and projects are not designed to withstand extreme storm events such as the Halloween Storm or the Blizzard of 1978, differences between the Blizzard of 1978, a "100-year" event at Boston, and the Halloween Storm of 1991, a "17-year" event, show that the Halloween Storm caused considerably more damage in certain areas such as Nantucket, Gloucester, and Rockport, even though it was "only" a "17-year" event. This is due to the fact that a storm's frequency is dependent on the elevations of the normal tide cycle and the time frame associated with the storm's arrival and duration. The Halloween Storm's maximum storm surge frequency was a 90-year event at Boston and a 10-year event at Portland. Storm surge frequencies for the Blizzard were 35-year and 4-year events at Boston and Portland, respectively. It is prudent to realize that severe coastal conditions may exist at a project site, regardless of the maximum stillwater level. Furthermore, storm surge and maximum stillwater levels are not the only parameters required to characterize the severity of a storm. The wave climate (height and period) should also be included in the characterization of a storm. For example, the wave climate was the major factor in contributing to damage, erosion, flooding, and associated economic losses within Cape Cod and Nantucket. The wave climate is not normally reflected in the return period associated with a storm.

2. This study provides a greater understanding of the spatial and temporal wave and water level conditions for the two storms. The information generated during this study, in particular the wave and water level hindcasting, is designed to be used as the framework for more detailed site-specific planning and engineering investigations and studies. It can be utilized to better understand the wave and water level conditions associated with extratropical events at a specific site. This information should be used as input to other engineering methods to resolve conditions at a specific onshore site. Since real-time nearshore wave characteristics are not available on a large scale, a hindcasting method was used to generate storm conditions at five nautical mile

intervals along the shoreline from Nantucket, Massachusetts north to Portland, Maine using existing wave transformation and propagation techniques. There are 73 stations at which hindcast wave and water level information is available for the Blizzard and the Halloween Storm. This information may be obtained by contacting the Corps of Engineers, New England Division.

In general, through comparisons of observed and hindcast wave and water level information, the Halloween Storm was a more intense event over the southern portion of the study area (Cape Cod, Nantucket), while the Blizzard of 1978 appeared to be more intense in the northern portions of the study area (New Hampshire, Maine).

Within the limitations of the hindcasting models, the results of the wave hindcast are reasonably accurate when compared to nearby NOAA wave data buoys and are an adequate representation of offshore conditions. The hindcast wave height and period associated with the Halloween Storm frequently exceeded those used within flood insurance studies developed by FEMA. Therefore, it is quite possible that the Halloween storm waves also exceeded the anticipated flood boundaries previously established within the flood insurance studies. However, further refinement of wave characteristics associated with the Halloween Storm is required for a detailed comparison with the wave envelope developed in the flood insurance studies.

Hindcast water levels are consistently near or greater than the 100-year stillwater levels determined in the flood insurance studies. However, this does not correspond with tide gage readings at Boston and Portland which indicated that the Halloween Storm was less than a 20-year event at both locations. As previously described, the hindcast water levels for the Halloween Storm do not include shoreline flooding of normally dry areas. It does not account for flooding caused by the combination of water levels and wave heights as the flood insurance studies do. Furthermore, the hindcast results are for particular points offshore, not at the shoreline as the flood insurance study results are. Therefore, more detailed water level analysis of the Halloween Storm is required to obtain comparable results along the shoreline, such as at the transects described within the flood insurance studies. Without further refinement, the wave and water level hindcast results are inconclusive for comparing to the 100-year flood boundary developed in the flood insurance studies. FEMA uses wave parameters that statistically represent a 100-year tropical or extratropical storm event, and therefore believe that revisions to the delineation of flood boundaries are not warranted. They also believe the 100-year flood boundaries and wave envelopes defined in the flood insurance studies are adequate representations of typical 100-year water levels and wave characteristics.

While the wave and water level climates generated during this study are "event specific" and don't necessarily represent a "typical" northeaster or extratropical storm, these two events are considered to be the storms of record in the New England region due to the severity of damages and overall intensity of the storm systems. Therefore, the

information contained in this report represents an "extreme" condition against which various shore protection measures and emergency management techniques can be gaged.

The meetings held with Massachusetts, New Hampshire, and Maine officials to discuss the Halloween Storm's effects also stressed the need for more site-specific studies of areas which consistently exhibit flooding, erosion and damage associated with severe extratropical storms. The economic assessment of losses and damages shows that there are large differences in the level of FEMA disaster reimbursements distributed to municipalities and private insurance payments for various areas. An in-depth analysis of insurance claims, payments and reimbursements along with further wave and water level climate modeling must be accomplished to answer questions such as, "...What coastal parameters (wave height, period, etc.) were the primary cause of damages within a specific area?...".

3. The intensity and track of the Halloween Storm are the result of numerous meteorological conditions which contributed to its development, severity, and characteristics. It is impossible to determine whether the meteorological conditions which resulted in this storm will ever occur again, however, it is fairly certain that storms of this magnitude could continue to develop and threaten the New England coastline. The results of the wave and water level climate hindcast has determined extreme conditions on a gross scale which may be applied to more site-specific areas to analyze the effects of storms of this magnitude. Although all storms are unique in character and nature, they all produce measurable results along the shoreline. Therefore, further detailed monitoring of coastal processes using real-time data acquisition rather than hindcasting methods is desirable and required for a more accurate representation of offshore conditions.

4. Certain areas of the New England coastline will continue to experience flooding, erosion, and damage from extratropical events such as the Halloween Storm and Blizzard of 1978. However, Federal, State, and local agencies can better prepare for these events if the magnitude of a particular ocean storm can be related to possible impacts and associated effects. For example, the strength of hurricanes are classified based on the Saffir-Simpson Hurricane Intensity Scale, which also details the expected damage associated with a particular category thereby alerting the public to anticipate certain results. However, no such system is in place for extratropical storms which can be equally devastating to certain areas of New England.

VIII. RECOMMENDATIONS

The following recommendations are based on the conclusions identified in the previous section.

1. The frequency, or return period, of an event should be carefully identified and fully explained before this information is released to other agencies, emergency management personnel, the media and the general public.

2. While the data and information within this report provides a regional account of the contrast between two major storm events, it also shows the need for more site-specific evaluations, particularly on expected damages and impacts associated with extratropical storms. Therefore, site-specific studies should be identified and initiated to determine typical onshore wave and water level conditions and to identify specific causes of coastal related damages. This would require further coastal processes modeling at specific problem sites throughout New England and should be coordinated with various state planning agencies and the Federal Emergency Management Agency. This could be accomplished under existing Corps of Engineers programs such as the Section 22, Planning Assistance to States and Flood Plain Management Services programs.

A comparison between wave characteristics used by FEMA in flood insurance studies and the hindcast wave climate for the Halloween Storm shows that the wave parameters used in the flood insurance studies may not be indicative of waves generated by the Halloween Storm. Hindcast wave periods frequently exceeded the wave period used within the flood insurance studies. In some cases, hindcast wave heights also exceeded the range of wave heights examined in the flood insurance studies. It is apparent that further refinement of nearshore wave parameters associated with the Halloween Storm is required to compare to the wave envelope developed within the flood insurance studies.

Further refinement is also required for determining the shoreline water levels produced by the Halloween Storm for comparison with the results from FEMA's flood insurance studies. Although the hindcast water levels are near or greater than the 100-year stillwater levels identified by FEMA, the observed water levels at tide gages in Boston and Portland are comparable to an event with a return period of less than 20 years. Therefore, based on a gross comparison of Halloween Storm hindcast water levels and the 100-year stillwater elevations developed by FEMA for the flood insurance studies, it appears that the hindcast water level results are inconclusive and further refinement is required.

3. A similar evaluation such as that which has been accomplished within this study should be performed to compare the Halloween Storm with a more recent event (e.g., the December 1992 northeaster) for which comparable wave, water level, and economic loss data may be obtained. For example, wave climate information from the same NOAA wave data buoys can be obtained for direct comparison. Comparing two recent storms may also

yield more meaningful results, especially when comparing damages, claims, and insurance payments with the wave and water level climate. A more accurate representation is capable because: 1) differences in the existing number of flood insurance policies may not be as great as they probably were between 1978 and 1991, 2) there would be less of an influence on damages and erosion due to the implementation of new shore protection structures, and 3) in-situ wave and water level measurements are available and comparable for both storm events.

4. Reliable nearshore sea state conditions through wave gage monitoring and beach/shoreline surveys should be obtained. This information could be used to verify existing wave and water level hindcasting methods and serve planning and design purposes within New England Division.

5. The National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS) completed a Natural Disaster Survey Report for the Halloween Storm published in June 1992. The following are two of the recommendations made in their report.

a. There is a need for an adequate, reliable, and timely database of sea state conditions and water level measurements to provide accurate and timely coastal flood watches and warnings. This recommendation is for the NWS to install an adequate marine observational network which includes shallow wave height measurements.

b. The NOAA/NWS Damage Survey Team found that many coastal residents took no appropriate action to protect their property or evacuate because they were unaware of the Halloween Storm's intensity. The report recommends investigating the feasibility of developing an intensity scale for extratropical storms.

The Army Corps of Engineers, New England Division, in conjunction with the Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), should pursue cooperation with other agencies to aid in establishing a sea state conditions measurement system within New England and in developing and/or implementing an intensity scale for extratropical storms such as the Dolan-Davis classification system. This cooperation could be undertaken through a Memorandum of Understanding. This recommendation is also consistent with NOAA/NWS recommendations given above.

IX. ACKNOWLEDGMENTS

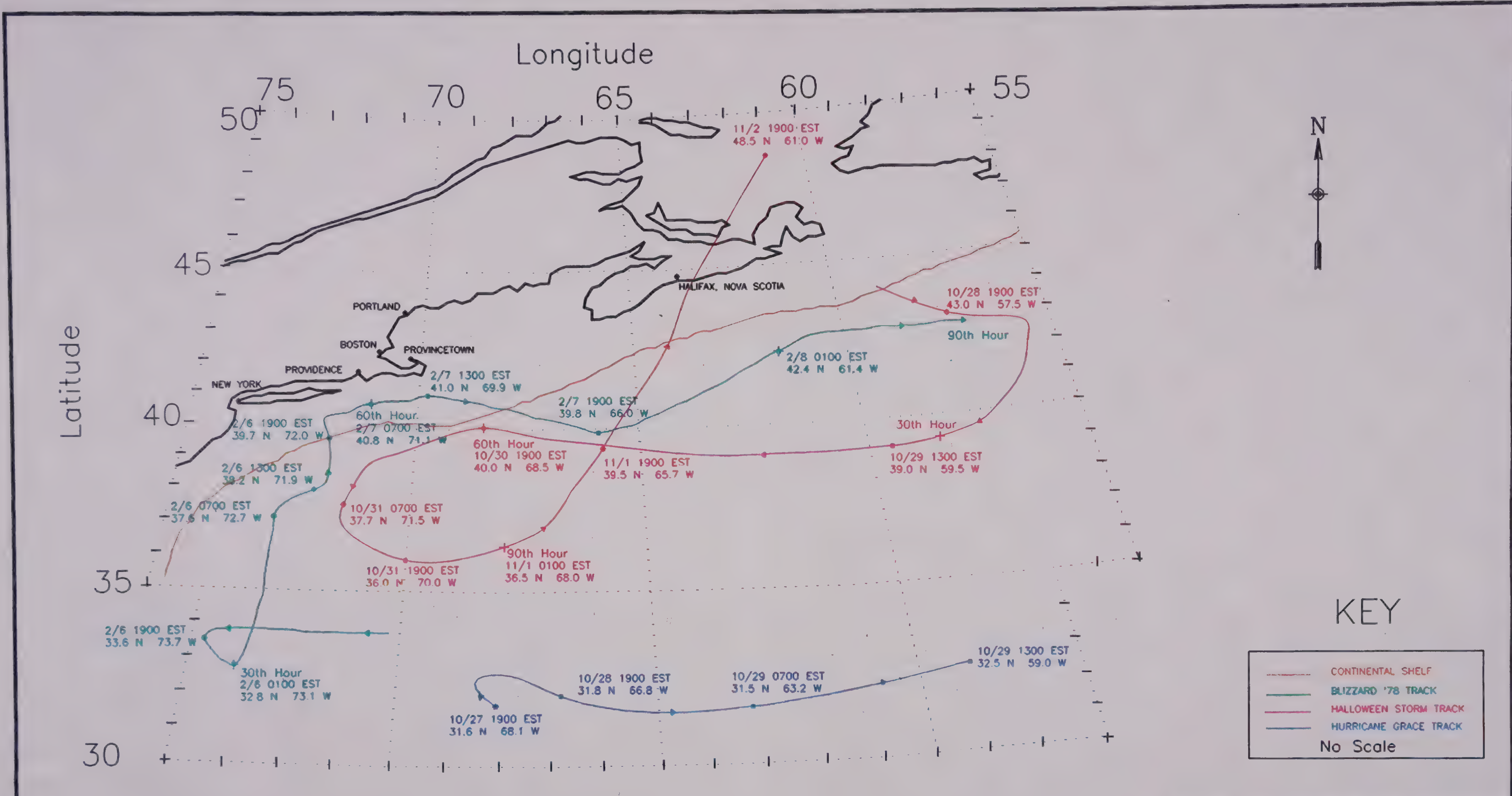
This report was developed and prepared by John H. Kedzierski, P.E., Project Manager. The report was prepared under the supervision and management of the following New England Division personnel:

Colonel Brink P. Miller, Division Engineer
Joseph L. Ignazio, Director of Planning
John C. Craig, Chief, Basin Management Division
John R. Kennelly, Chief, Long Range Planning Branch

Assistance was provided by Christine Davey (Basin Management Division), Edmund O'Leary (Impact Analysis Division), Steve Andon (Emergency Operations Branch), and Charles Wener (Water Control Division). The wave and water level hindcast was conducted by Dr. Jon M. Hubertz and William R. Curtis of the U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center.

Special thanks to Dr. Franklin W. Fessenden for the use of his erosion data and photographs of Nantucket and to Robert Thompson of the National Weather Service in Boston, Massachusetts for his contribution of meteorological data and information.

X. FIGURES



Halloween Coastal Storm Evaluation

STORM TRACK
FIGURE 1a

October 1993

U.S. Army Corps of Engineers, New England Division, Waltham, MA

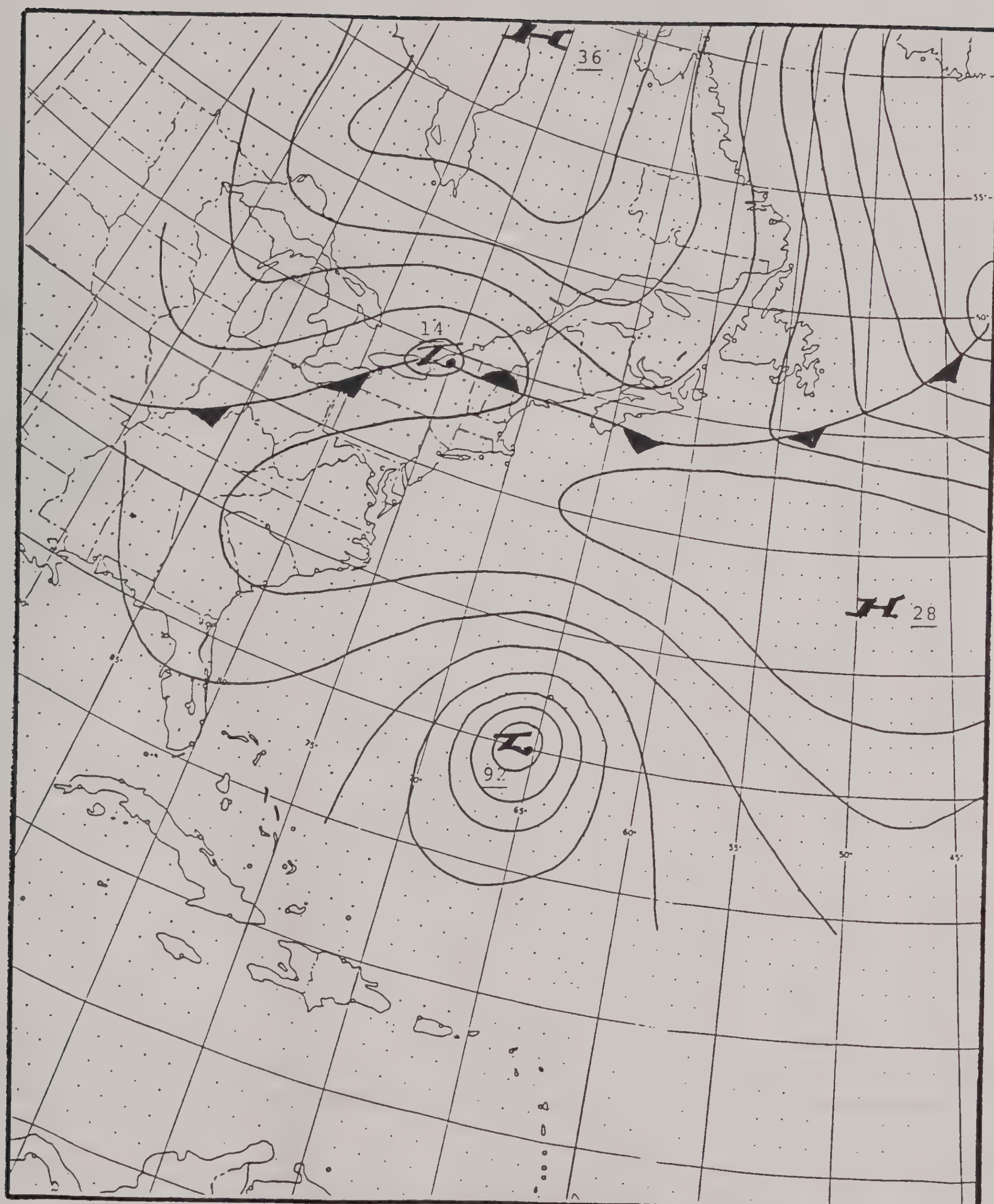


Figure 1b **1200 UTC Surface Analysis - 27 October 1991.**

Source: Natural Disaster Survey Report - The Halloween Nor'ester of 1991
NOAA/NWS, June 1992.

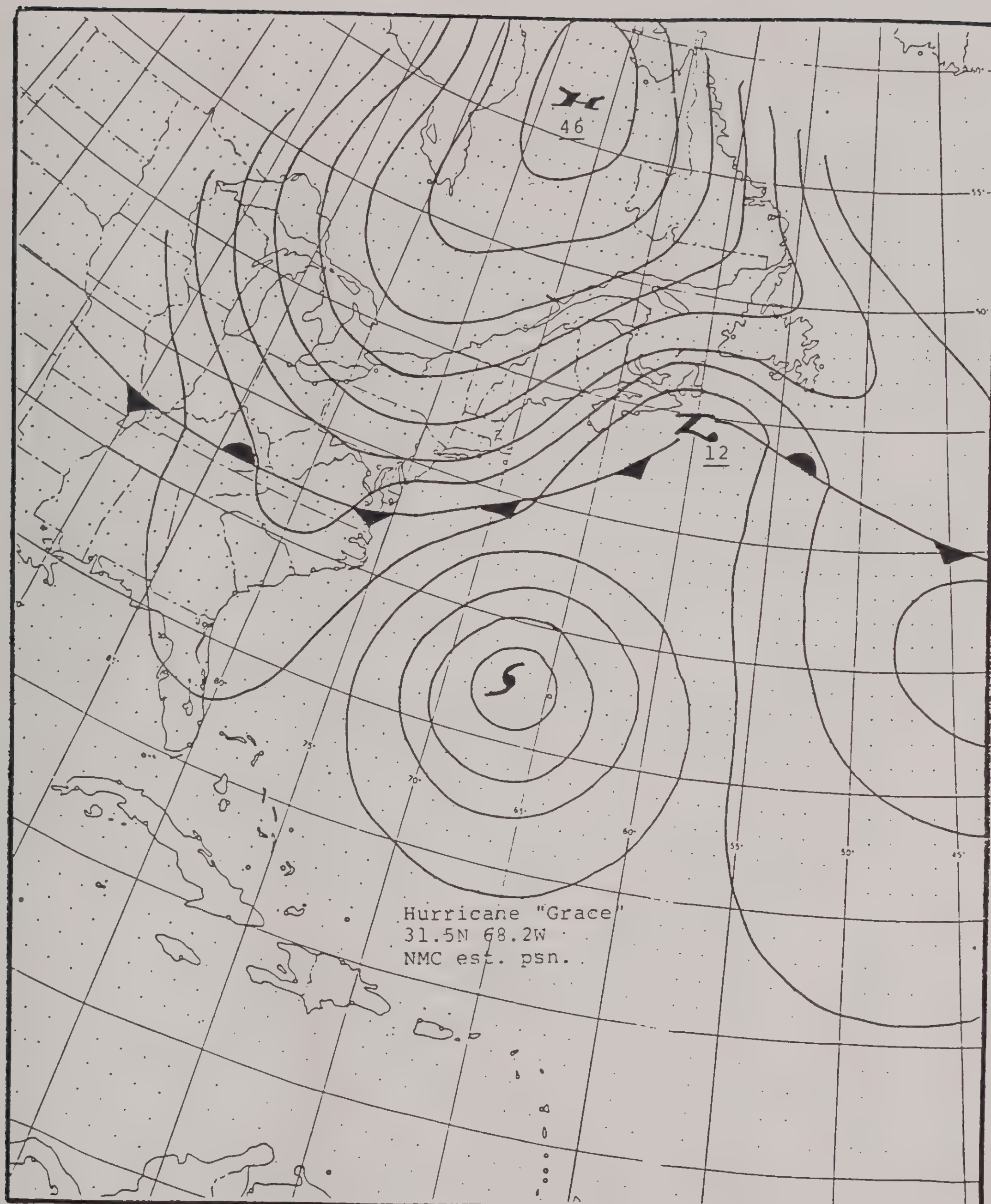


Figure 1c 1200 UTC Surface Analysis - 28 October 1991.

Source: Natural Disaster Survey Report - The Halloween Nor'ester of 1991
NOAA/NWS, June 1992.

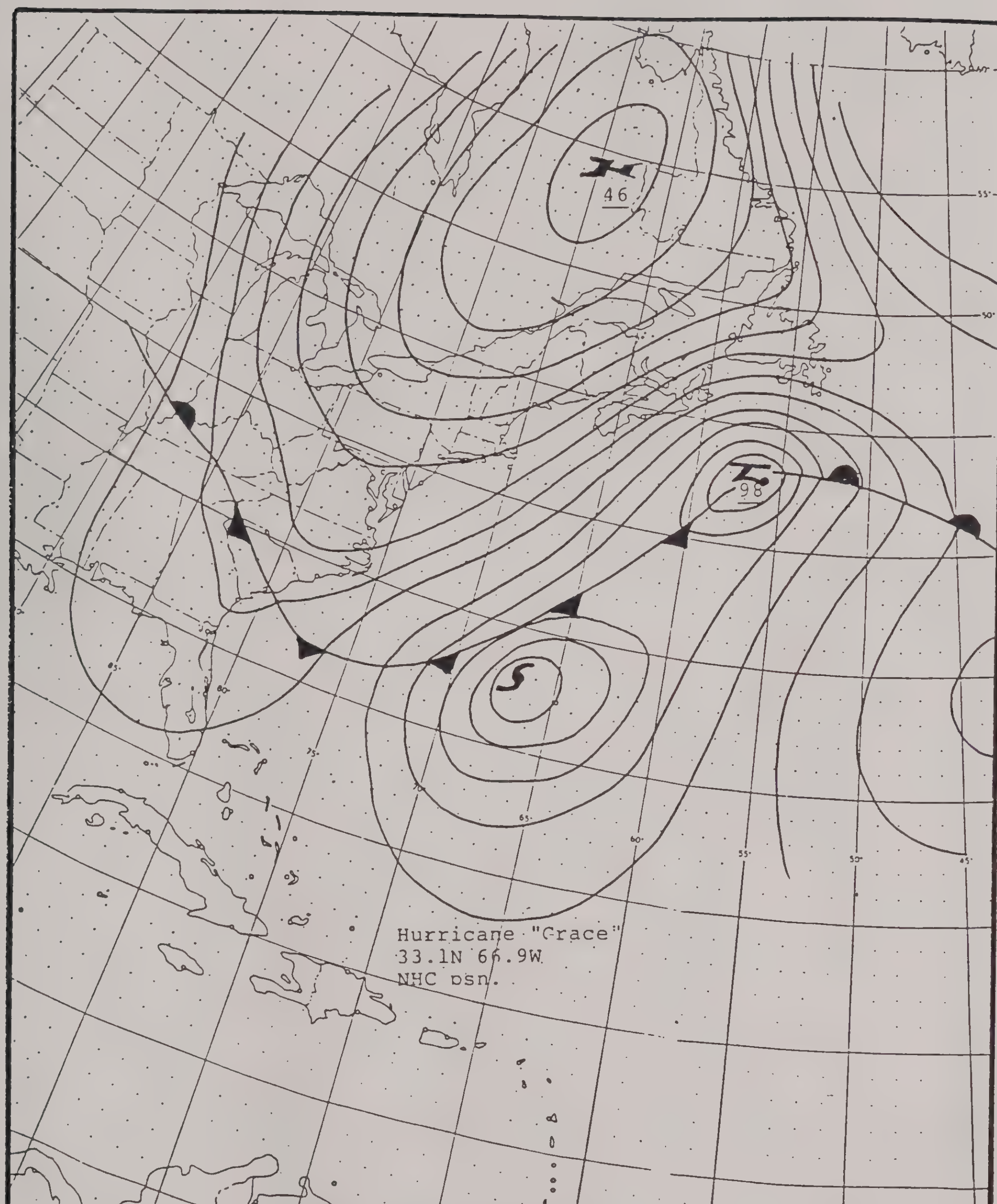


Figure 1d 0000 UTC Surface Analysis - 29 October 1991.

Source: Natural Disaster Survey Report - The Halloween Nor'ester of 1991
NOAA/NWS, June 1992.

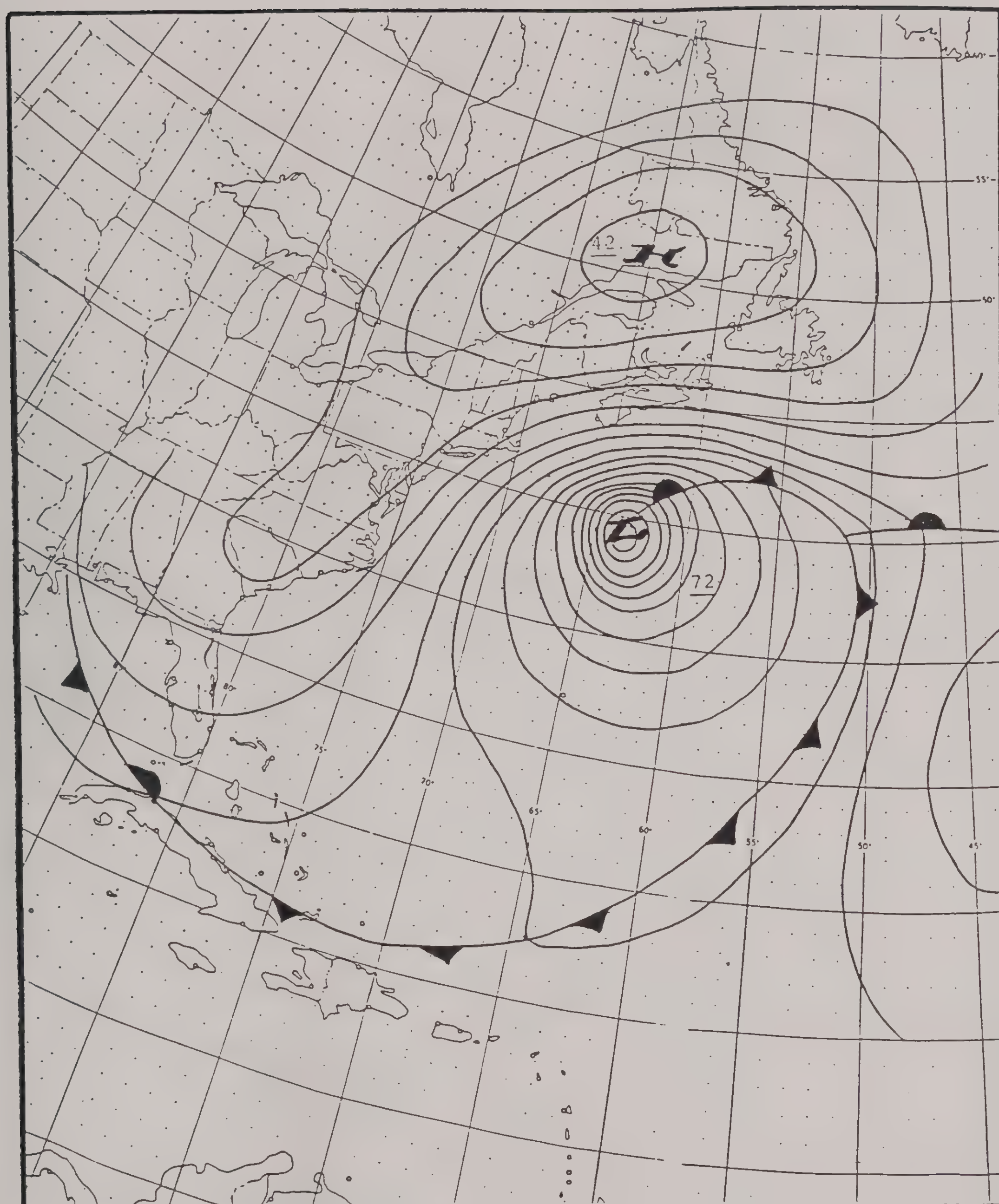


Figure 1e 1200 UTC Surface Analysis - 30 October 1991.

Source: Natural Disaster Survey Report - The Halloween Nor'ester of 1991
NOAA/NWS, June 1992.

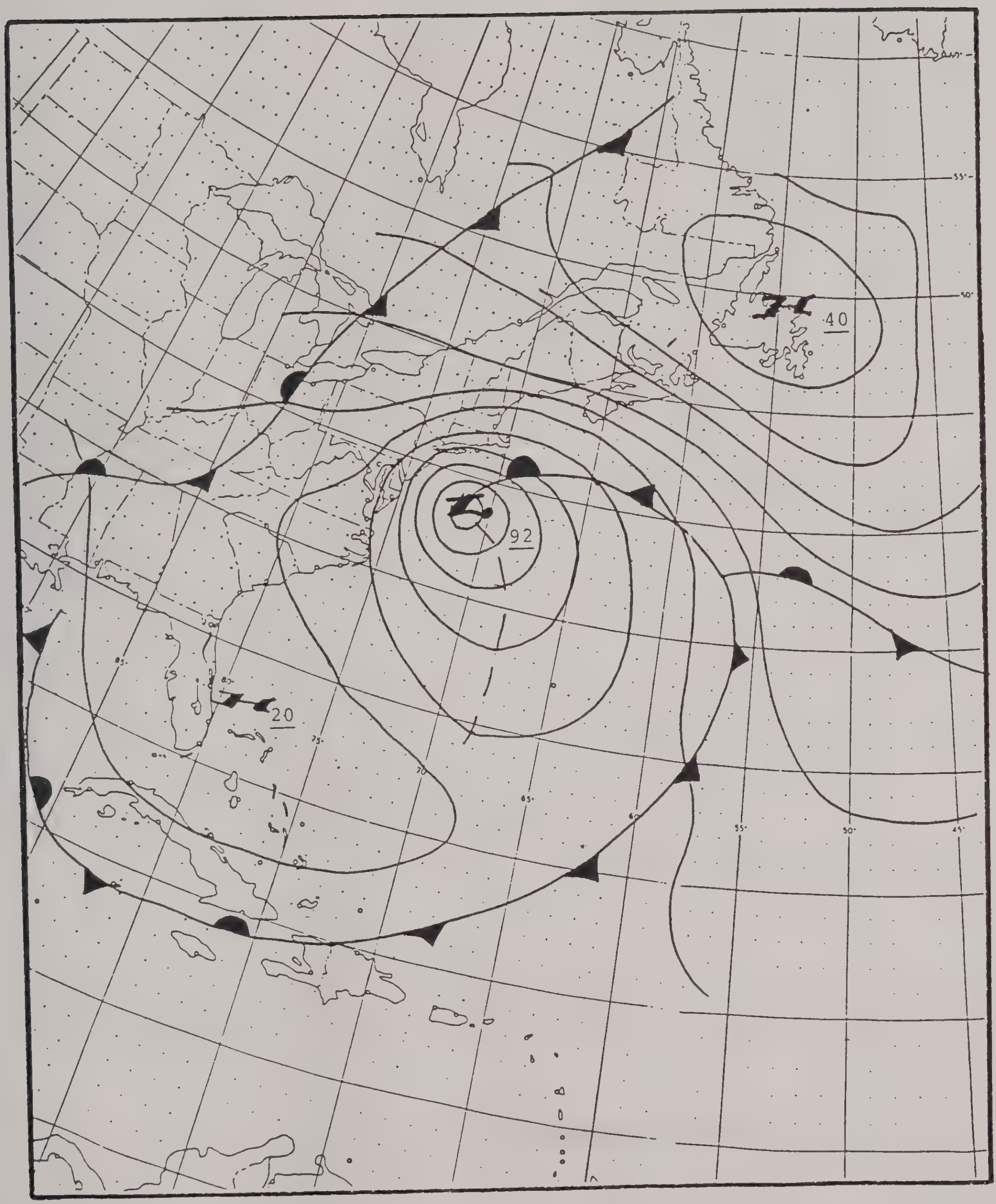


Figure 1f 1200 UTC Surface Analysis - 31 October 1991.

Source: Natural Disaster Survey Report - The Halloween Nor'ester of 1991
NOAA/NWS, June 1992.

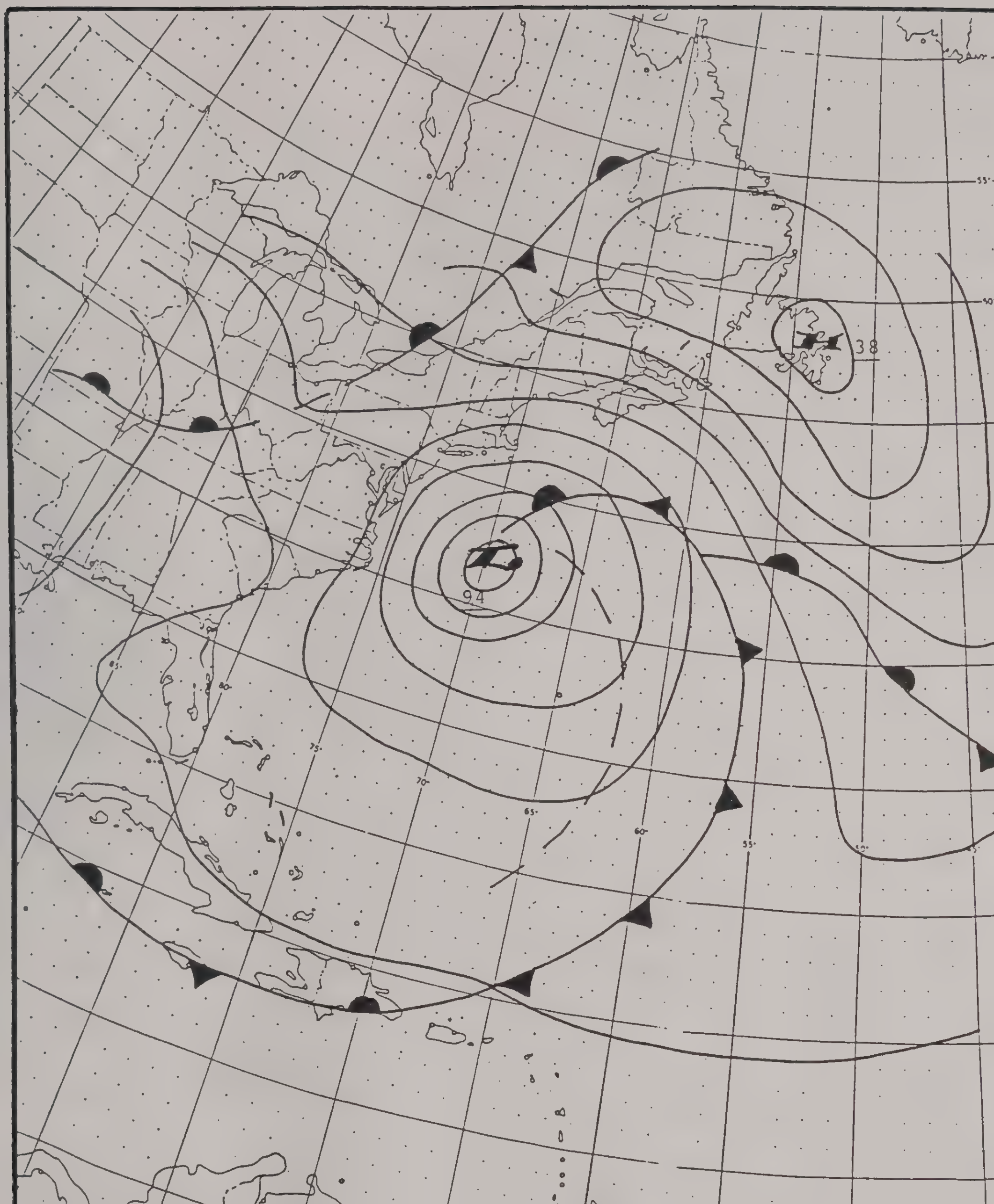


Figure 1g 1200 UTC Surface Analysis - 1 November 1991.

Source: Natural Disaster Survey Report - The Halloween Nor'ester of 1991
NOAA/NWS, June 1992.

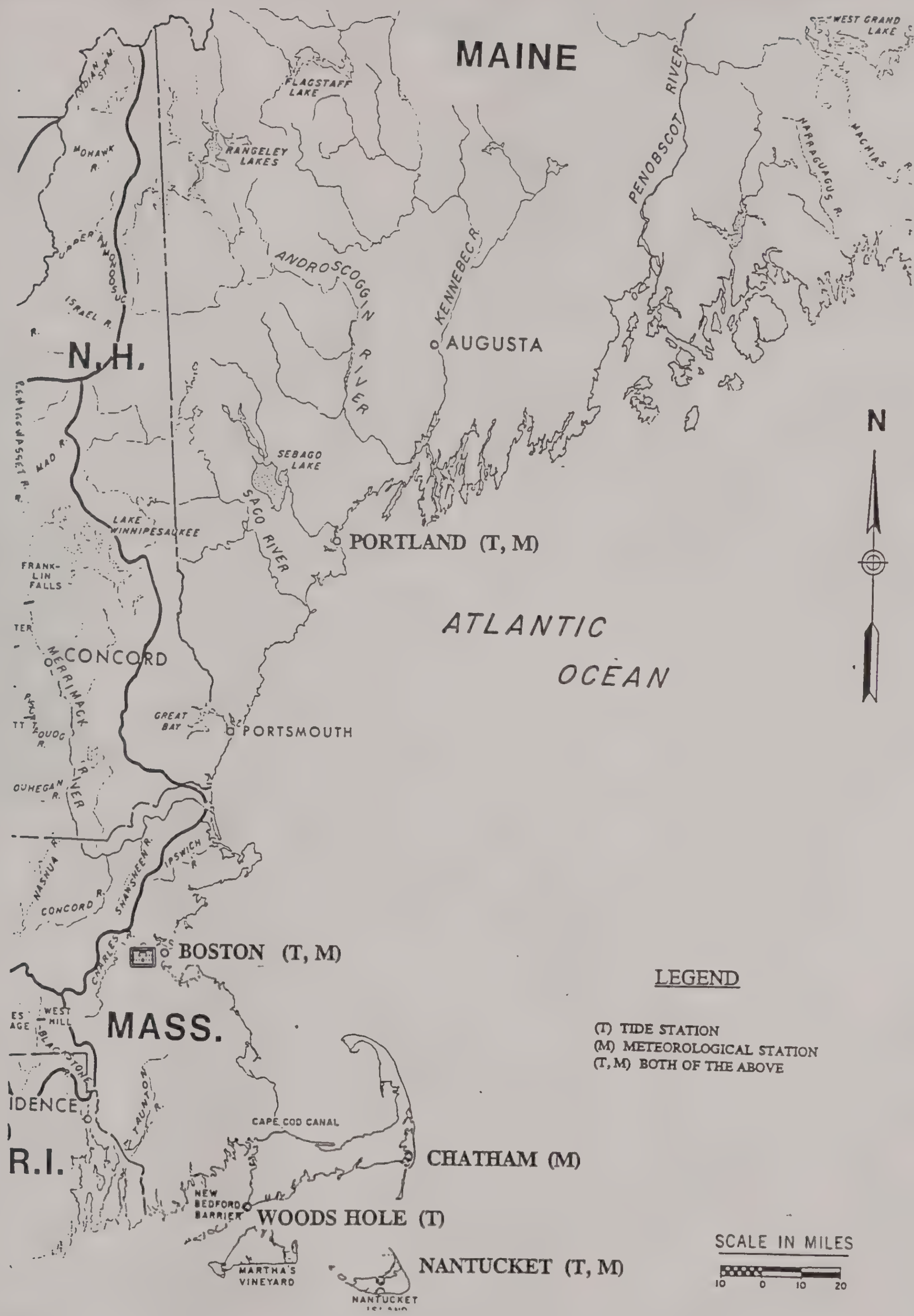


Figure 2

Meteorological & Tide Station Locations

New England Division

US Army Corps of Engineers

FIGURE 2a — PORTLAND, MAINE TIDES

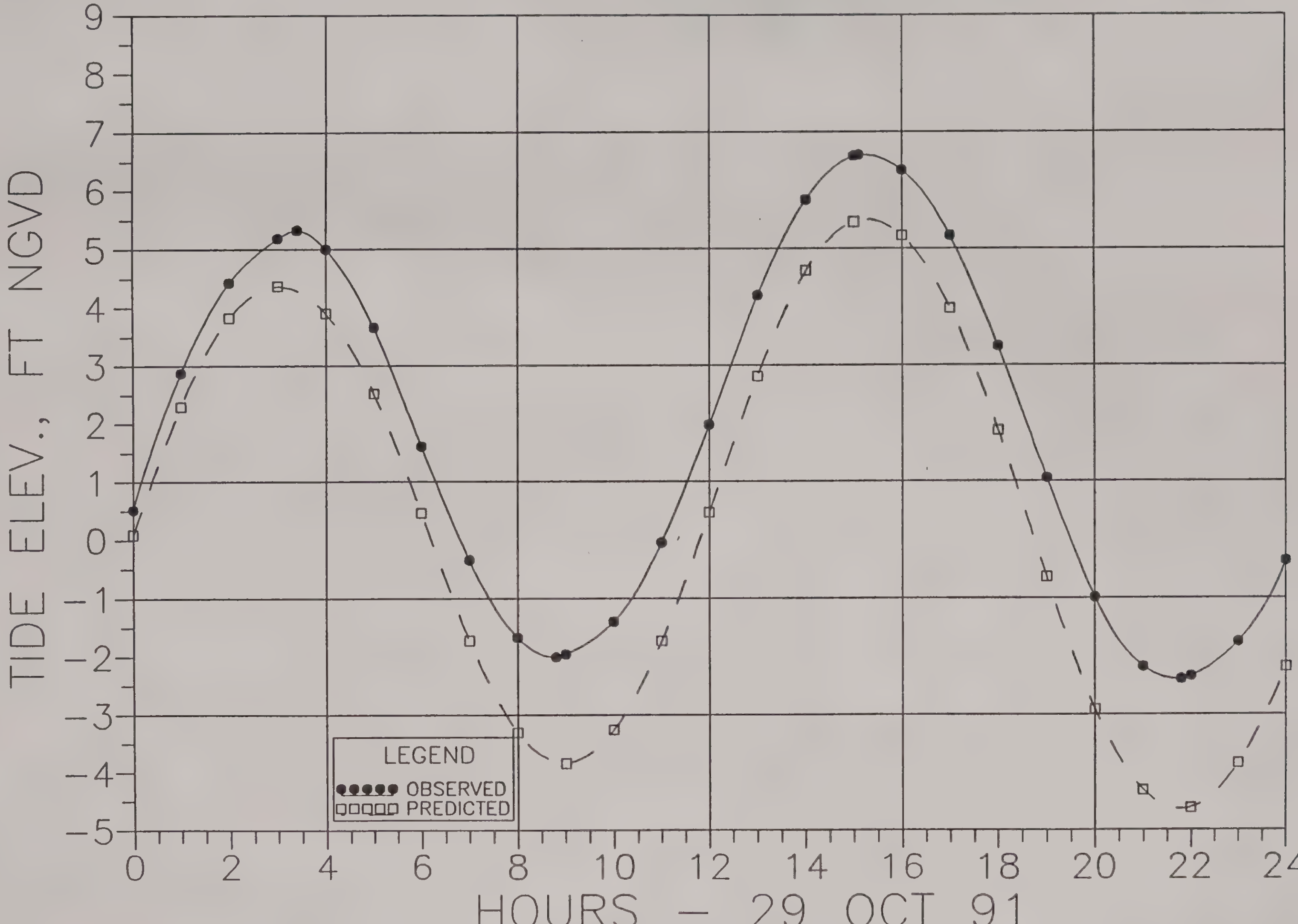


FIGURE 2b – PORTLAND, MAINE TIDES

MAX. OBSERVED = 8.2 FT NGVD (16.6 HRS)
MAX. STORM SURGE = 3.5 FT (11.2 HRS)

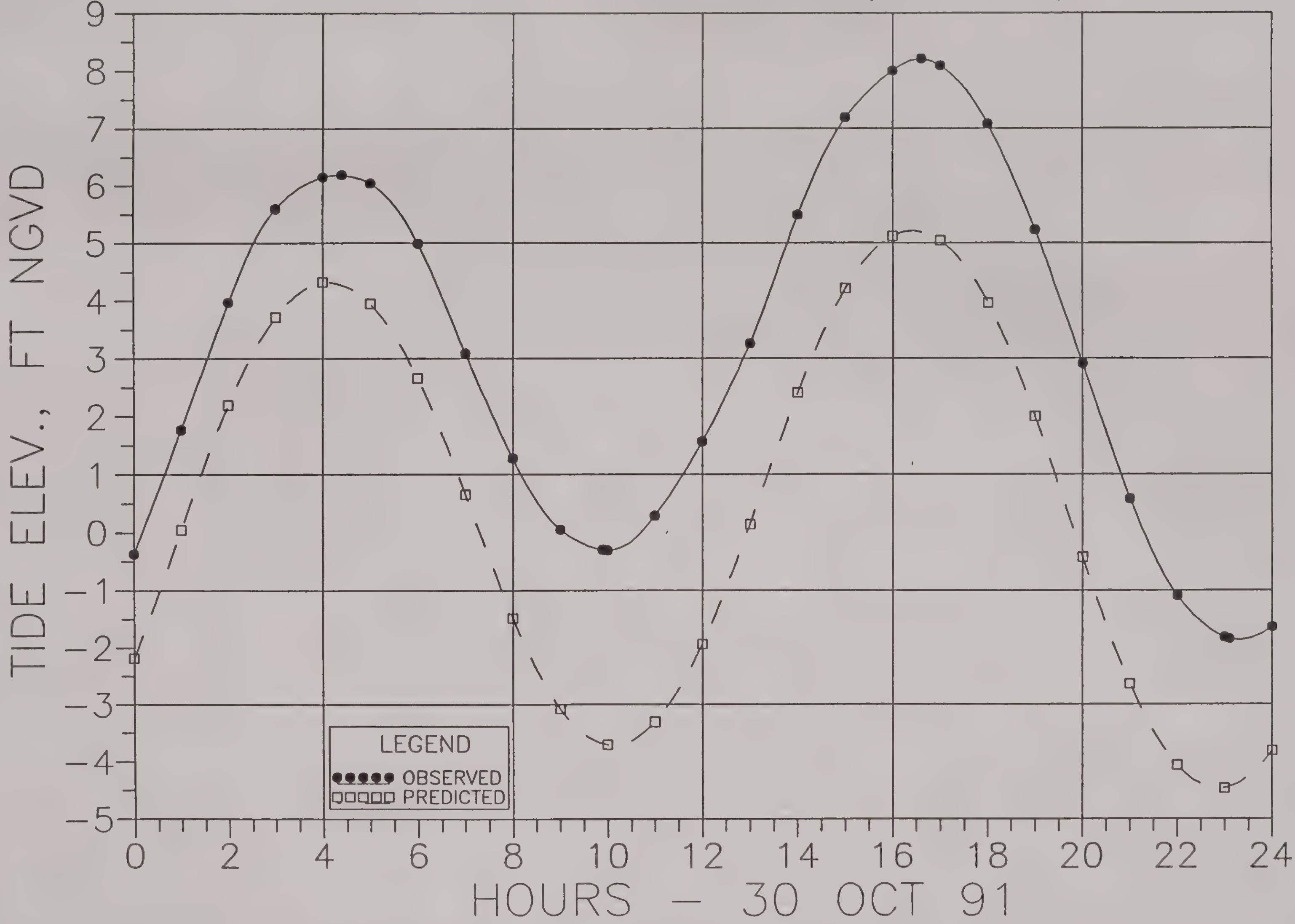


FIGURE 2c — PORTLAND, MAINE TIDES

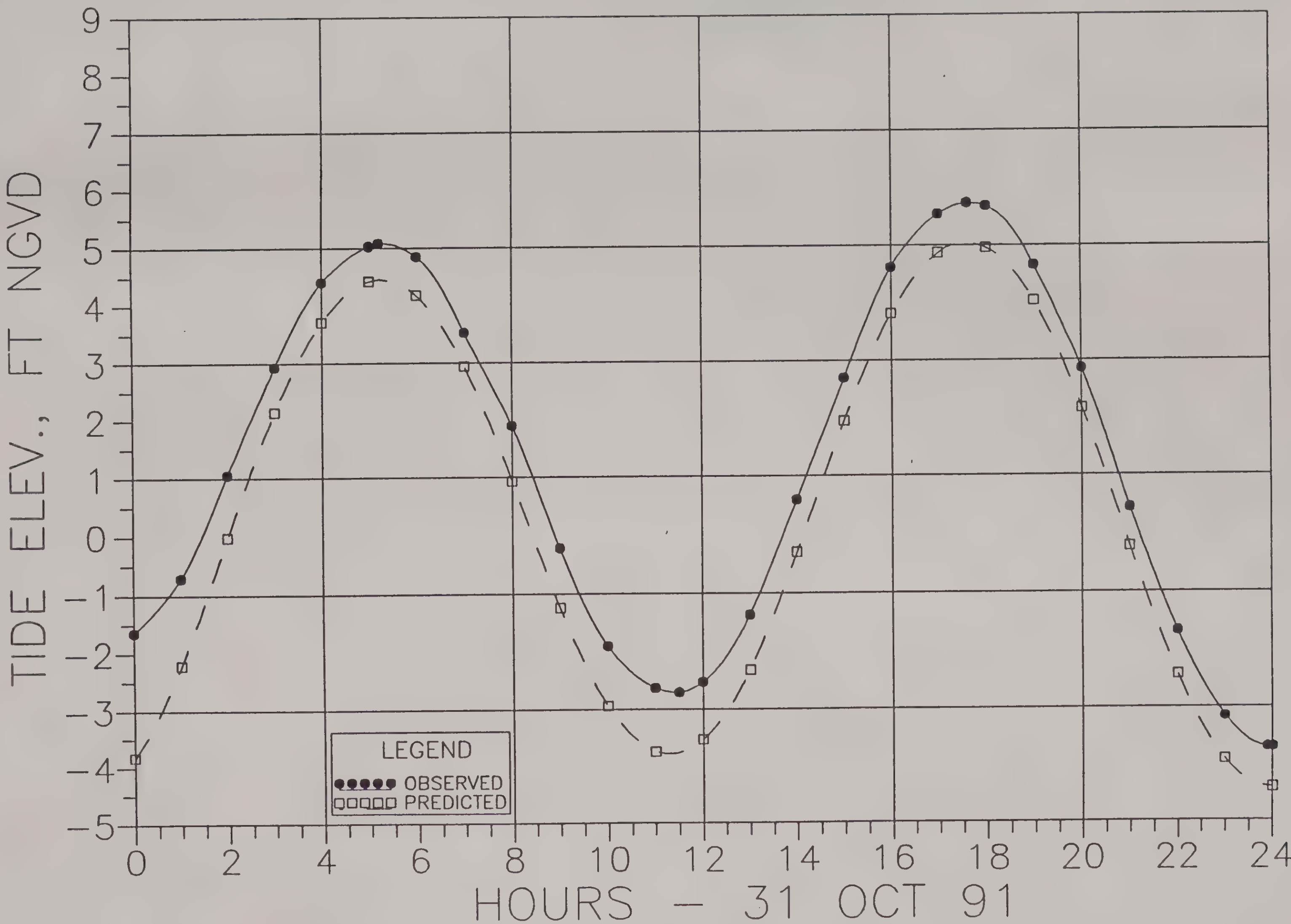


FIGURE 2d — PORTLAND, MAINE TIDES

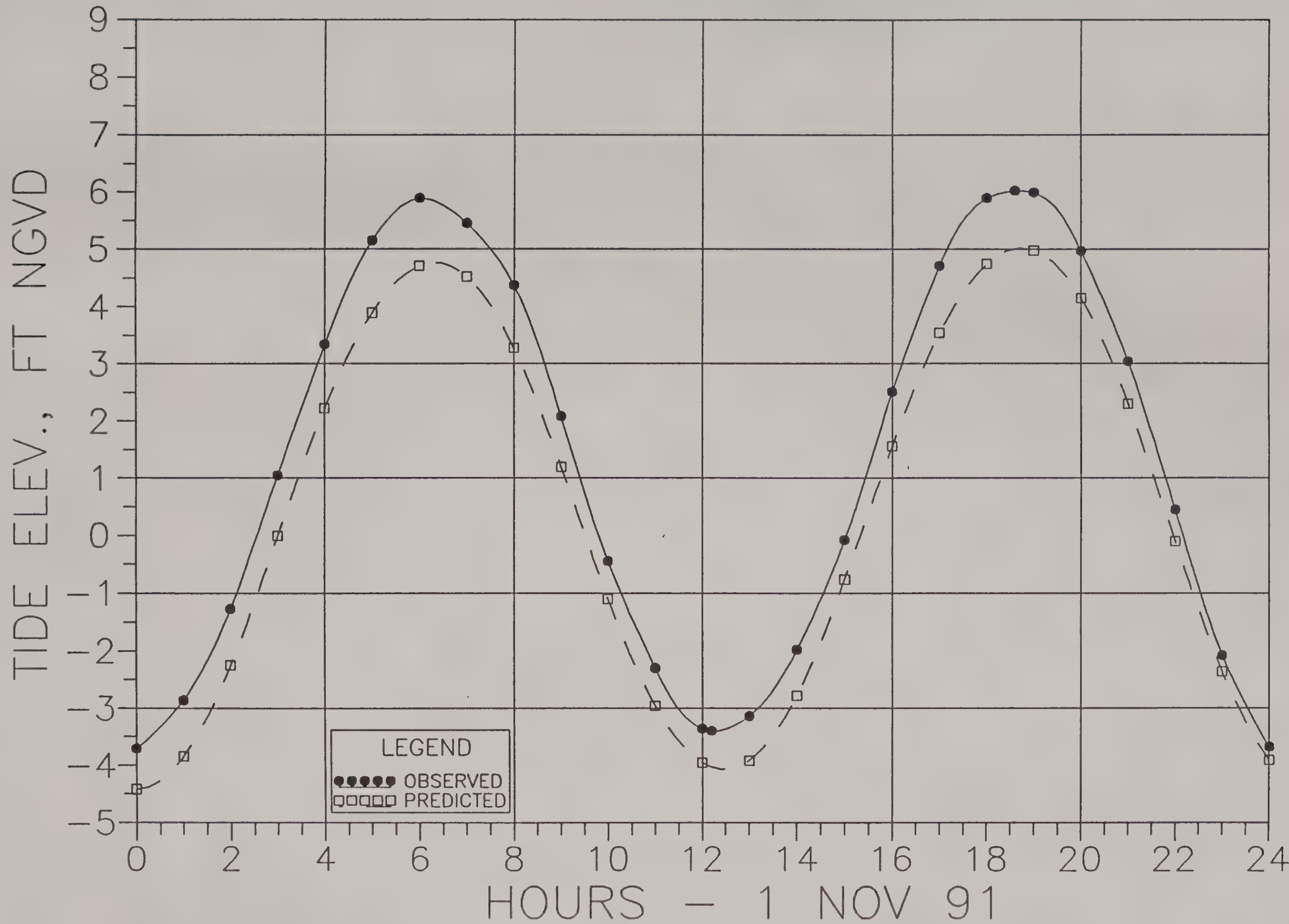


FIGURE 3a – BOSTON, MASS. TIDES

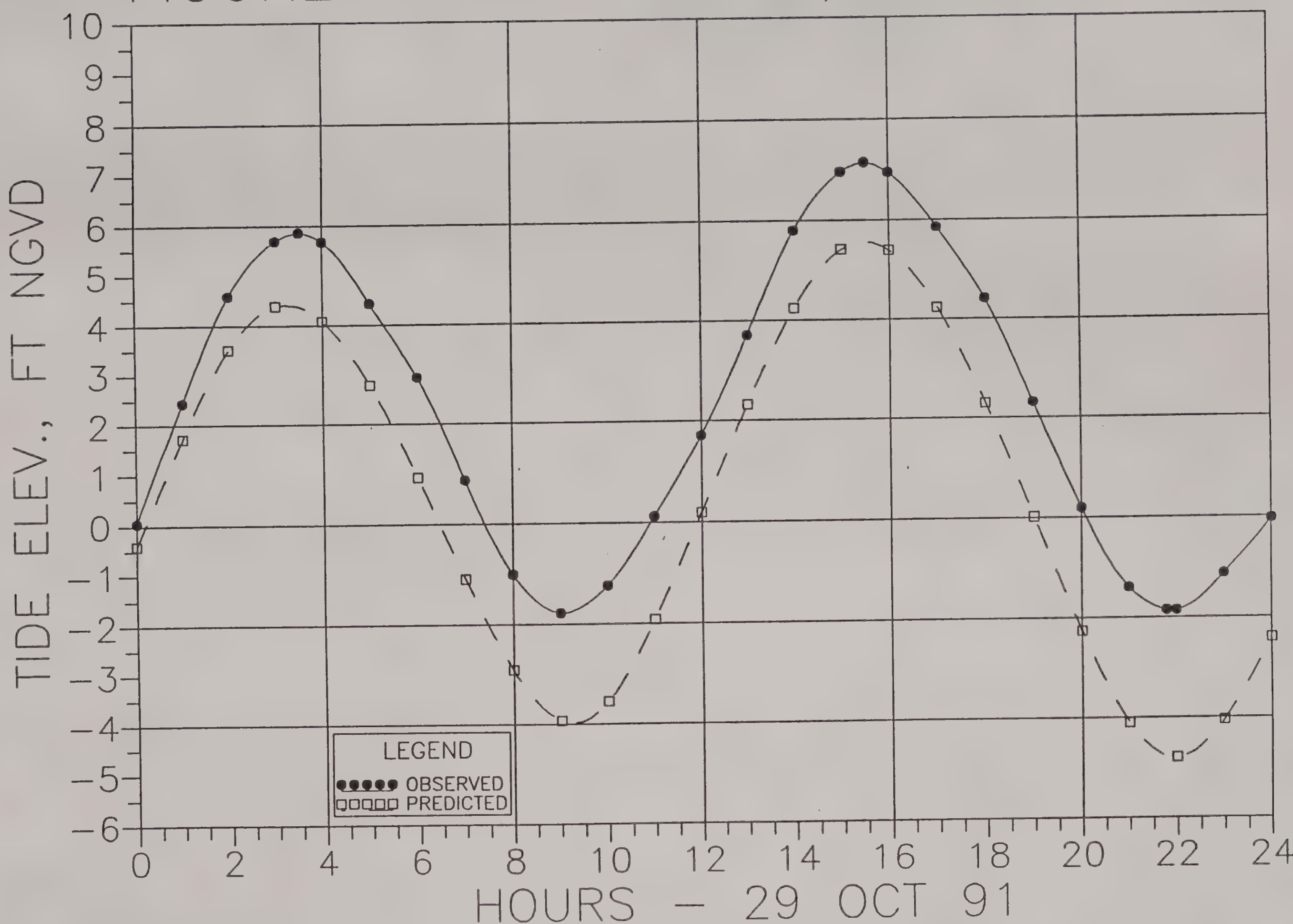


FIGURE 3b — BOSTON, MASS. TIDES

MAX. OBSERVED = 9.4 FT NGVD (16.9 HRS)
MAX. STORM SURGE = 5.1 FT (20.7 HRS)

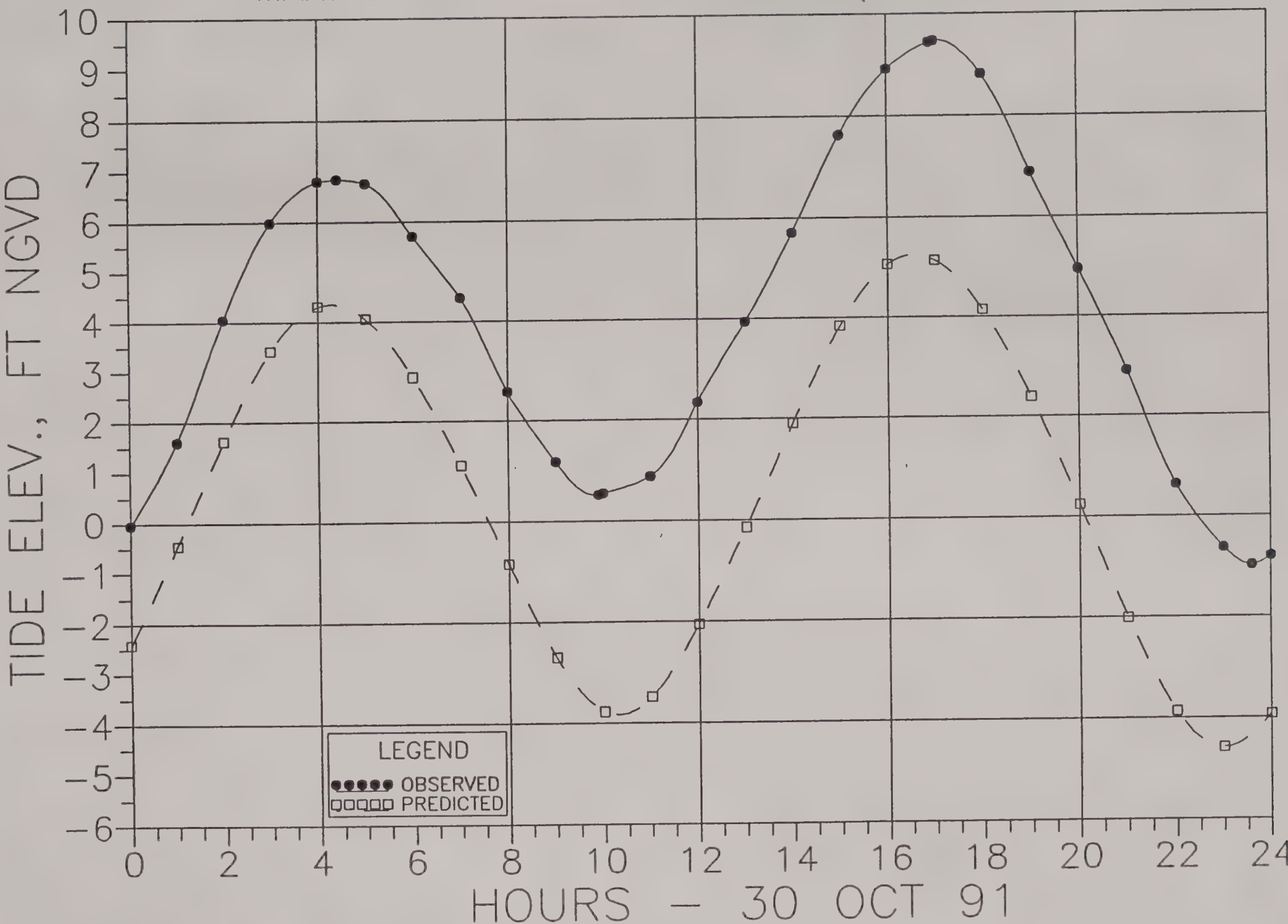


FIGURE 3c — BOSTON, MASS. TIDES

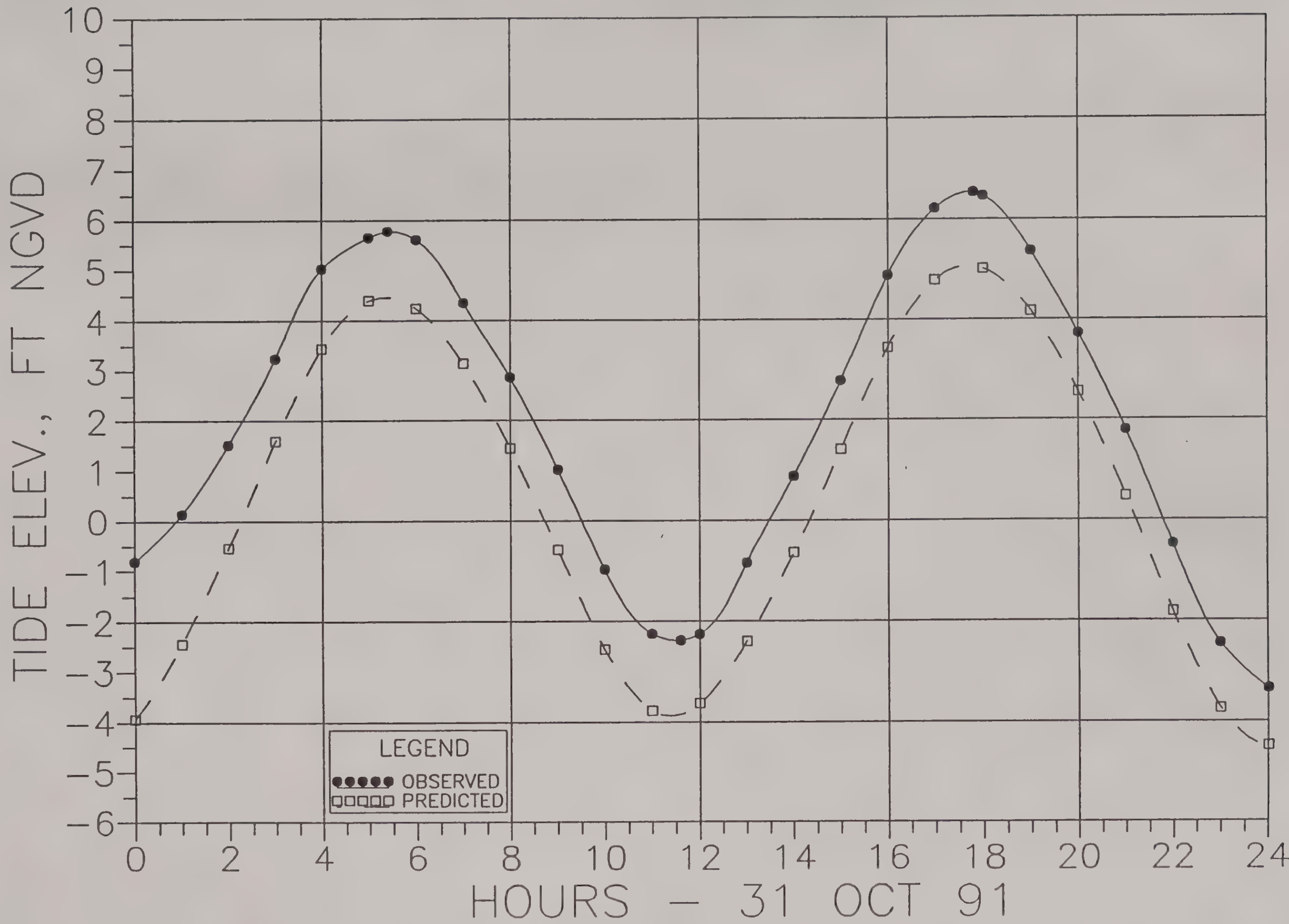


FIGURE 3d — BOSTON, MASS. TIDES

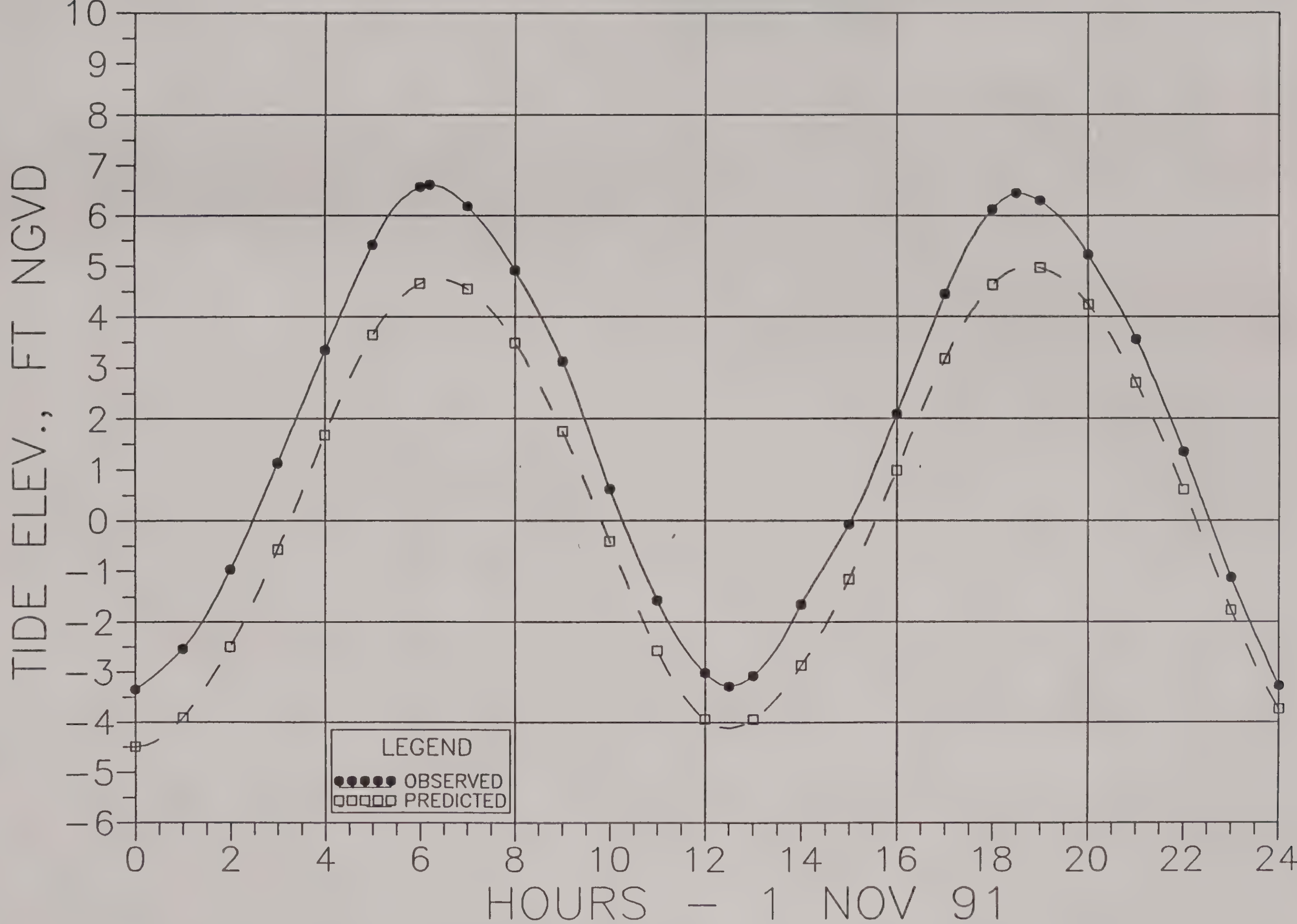


FIGURE 4a — NANTUCKET, MASS. TIDES

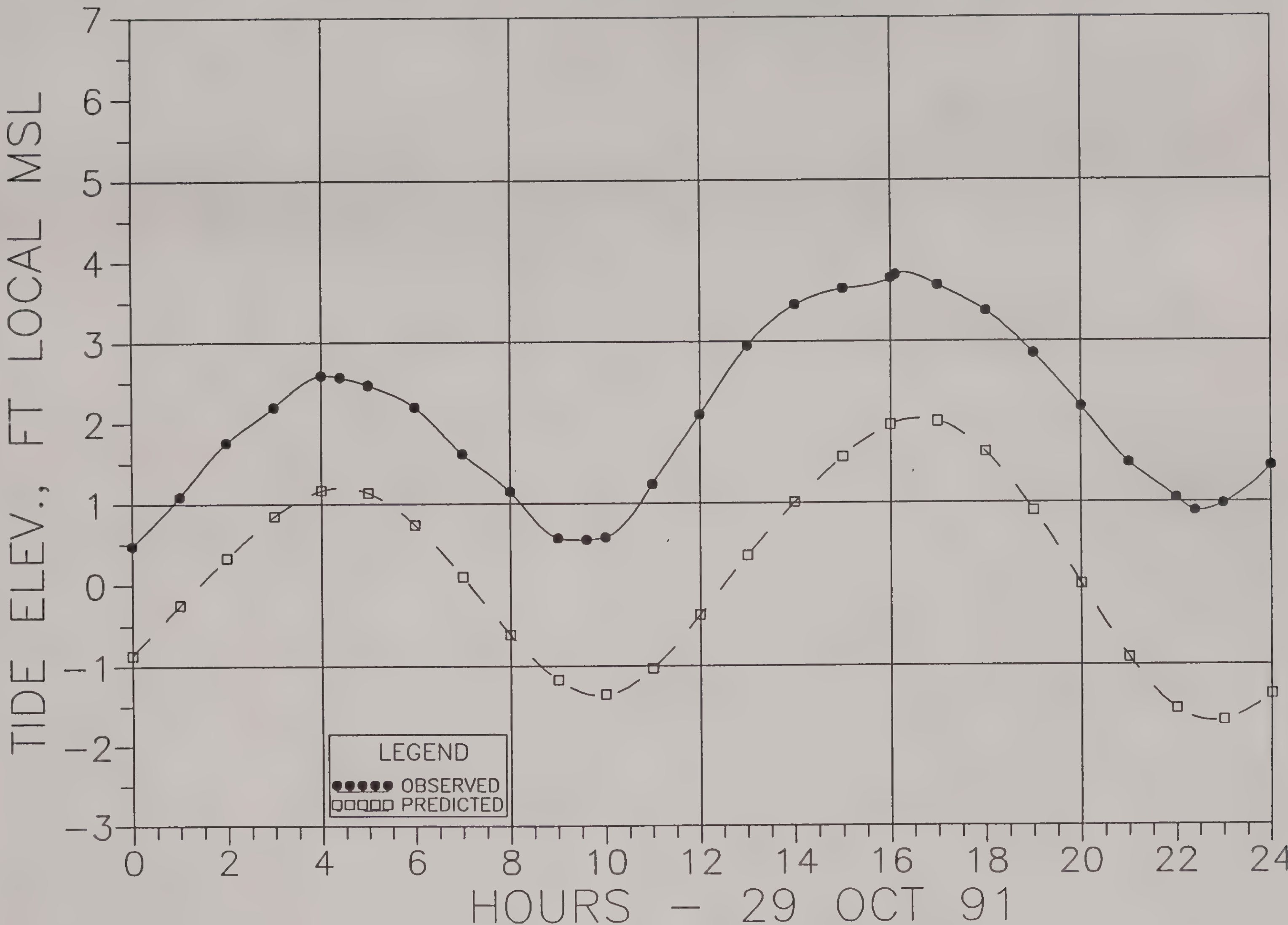


FIGURE 4b — NANTUCKET, MASS. TIDES

MAX. OBSERVED = 6.3 FT LOCAL MSL (17.5 HRS)
MAX. STORM SURGE = 4.6 FT (15.0 HRS)

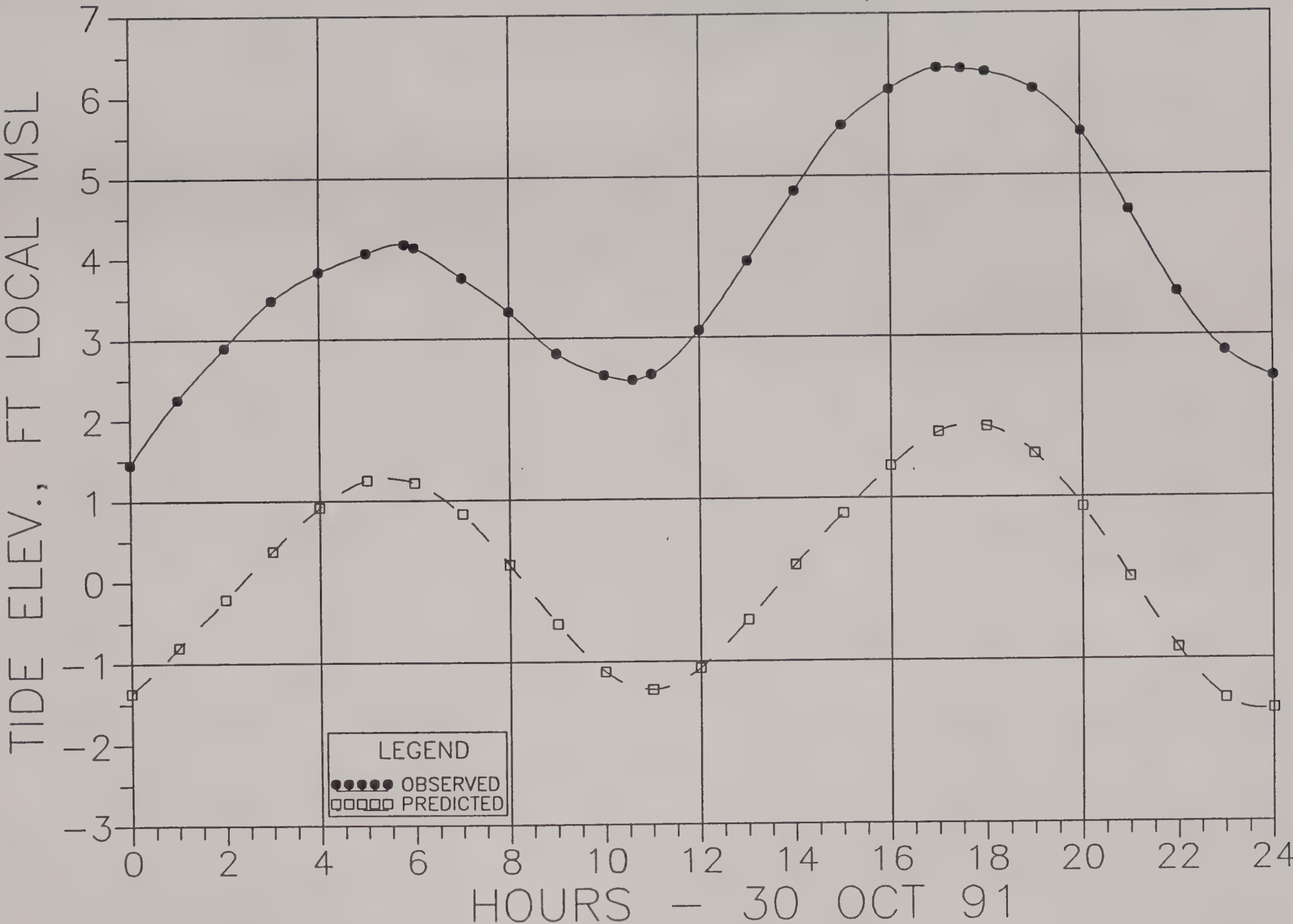


FIGURE 4c – NANTUCKET, MASS. TIDES

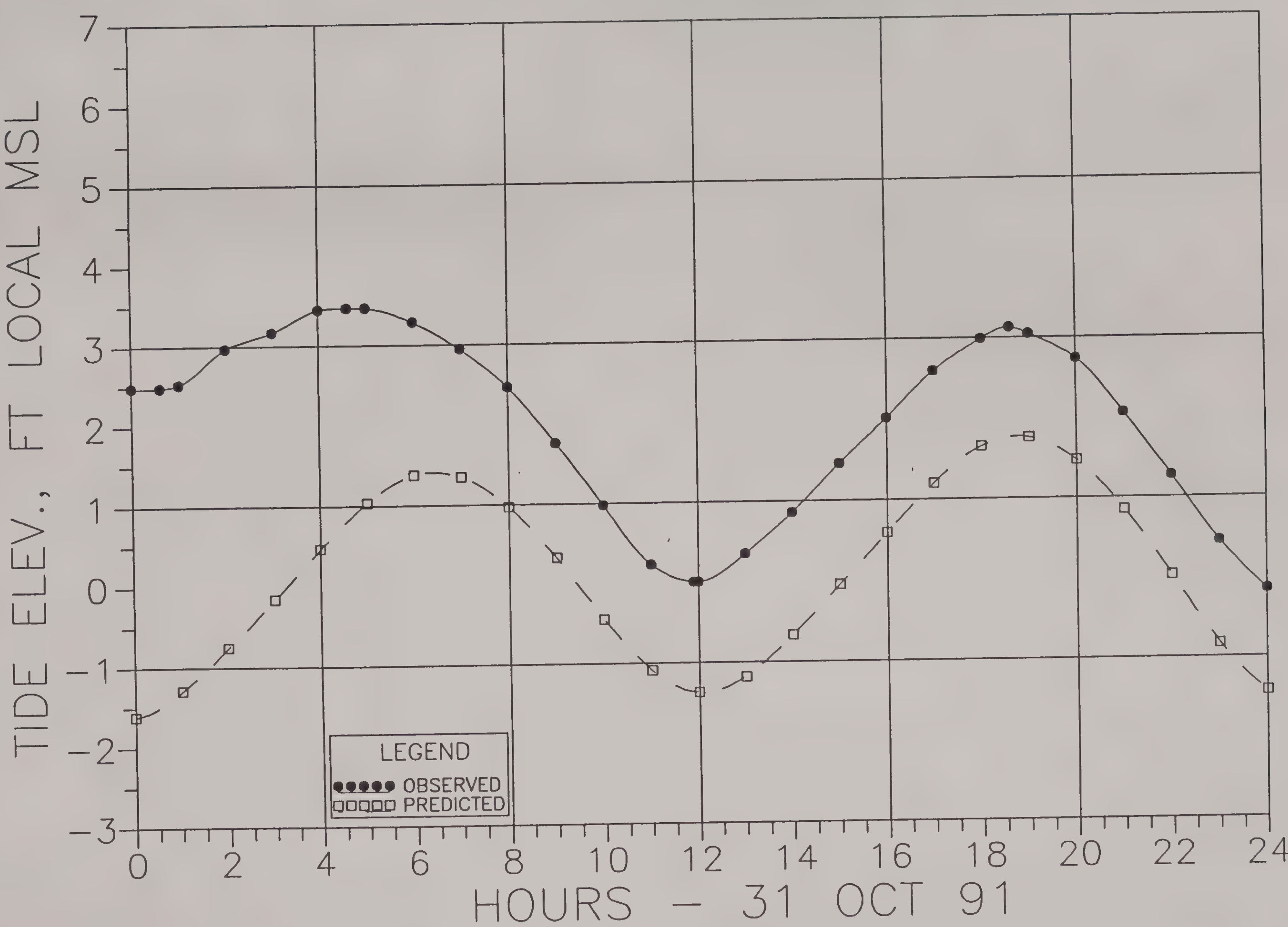


FIGURE 4d — NANTUCKET, MASS. TIDES

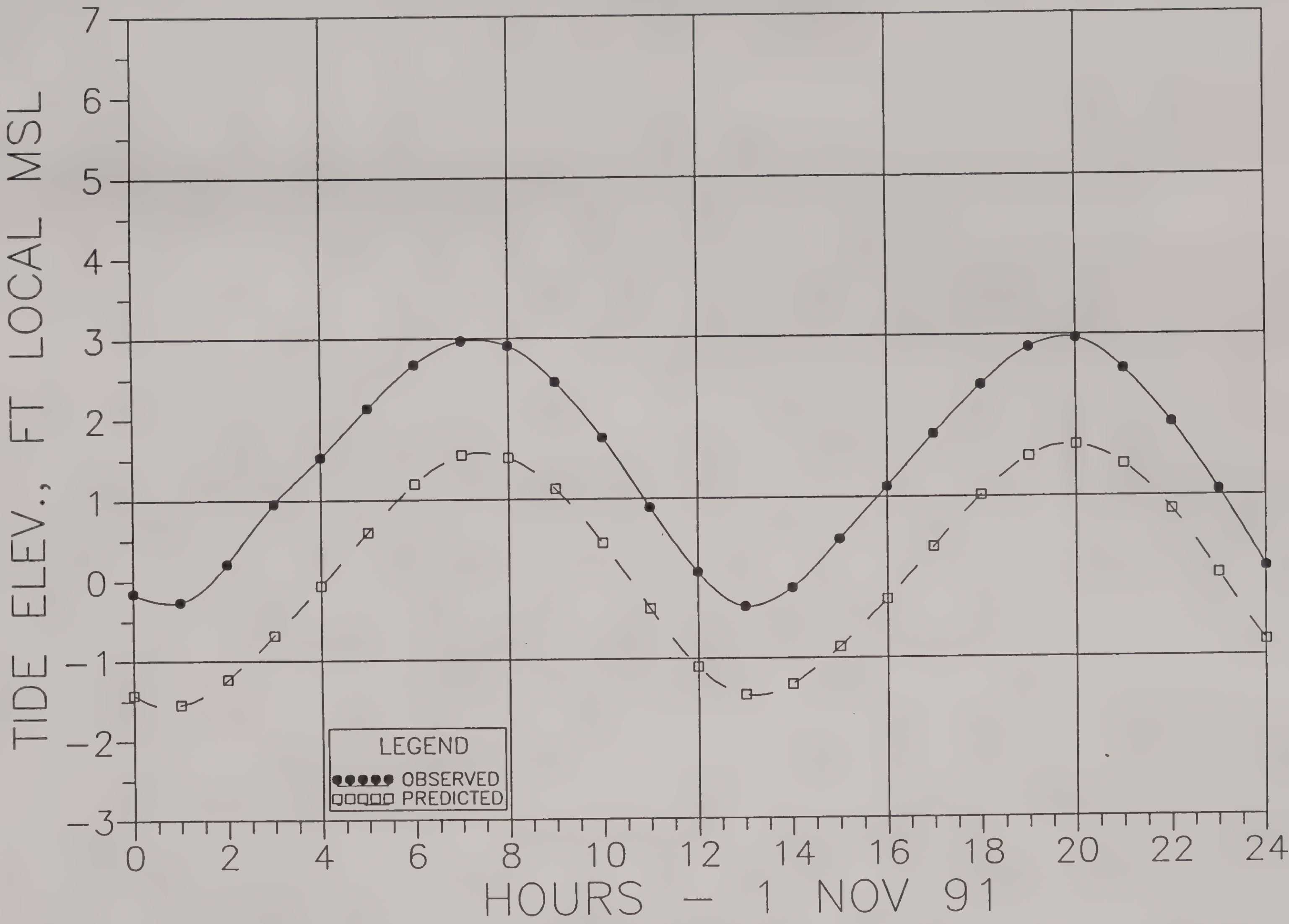


FIGURE 5a — WOODS HOLE, MASS. TIDES

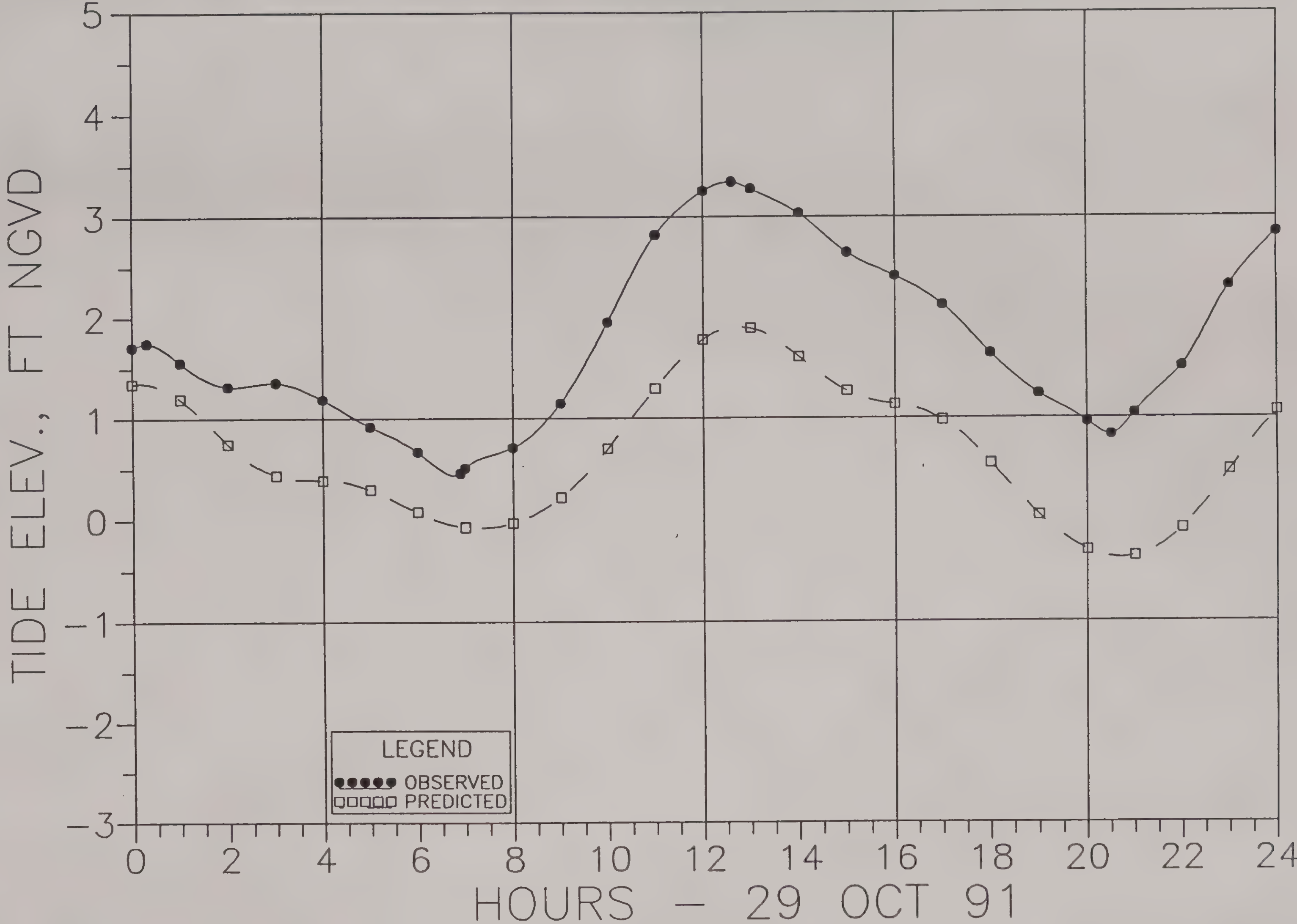


FIGURE 5b — WOODS HOLE, MASS. TIDES

MAX. STORM SURGE = 4.4 FT (23.3 HRS)

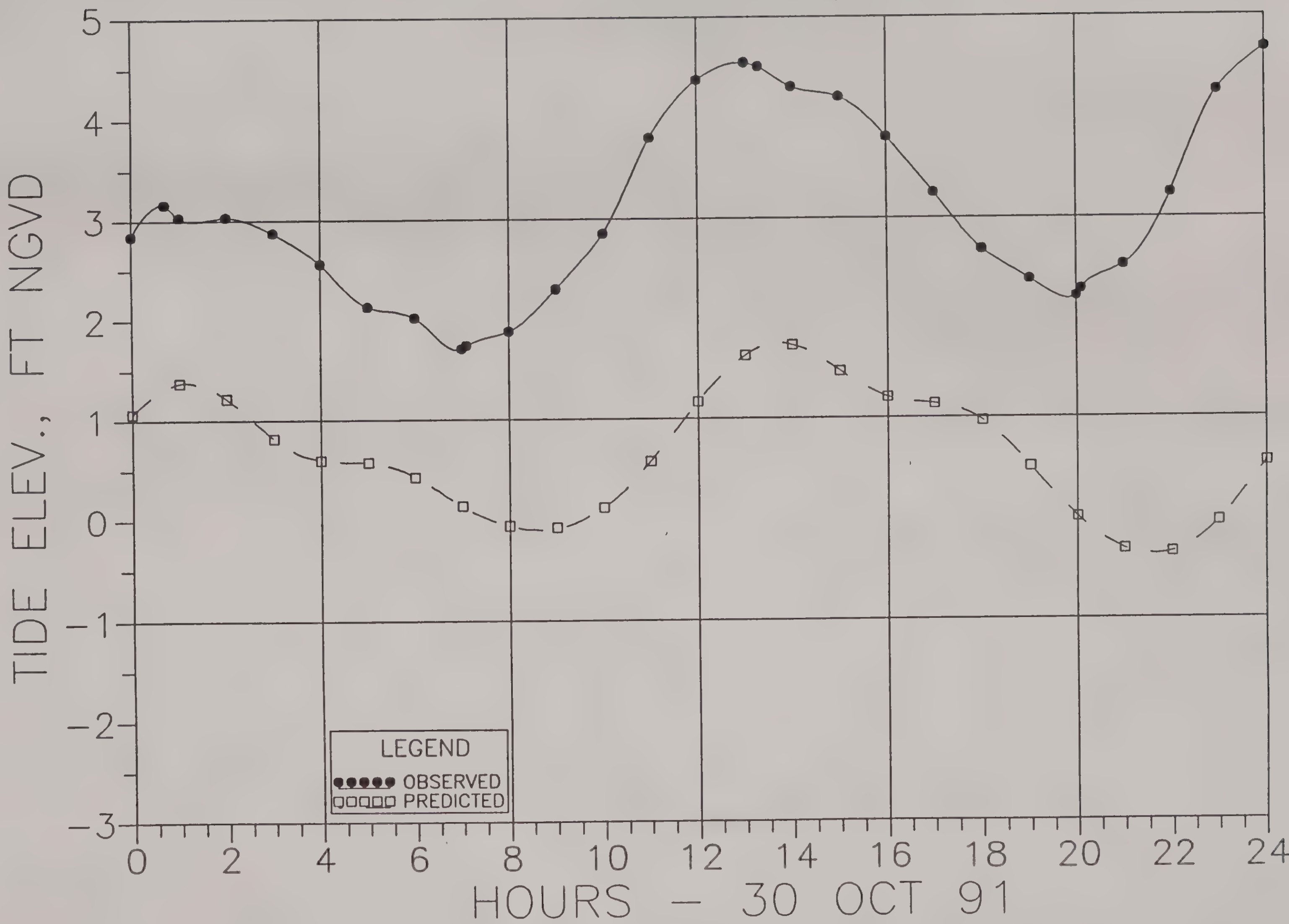


FIGURE 5c — WOODS HOLE, MASS. TIDES

MAX. OBSERVED = 4.8 FT NGVD (1.0 HRS)

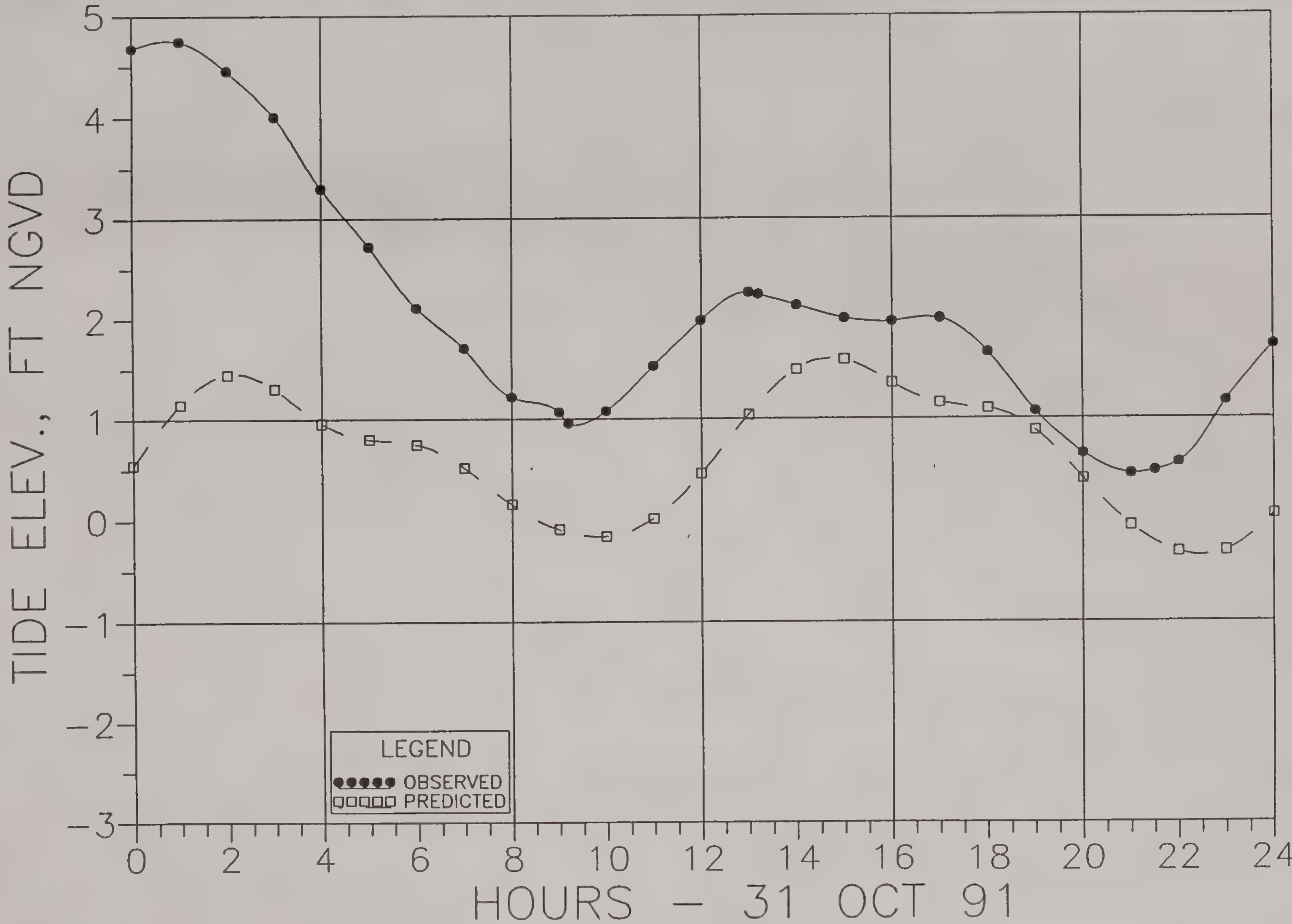


FIGURE 5d – WOODS HOLE, MASS. TIDES

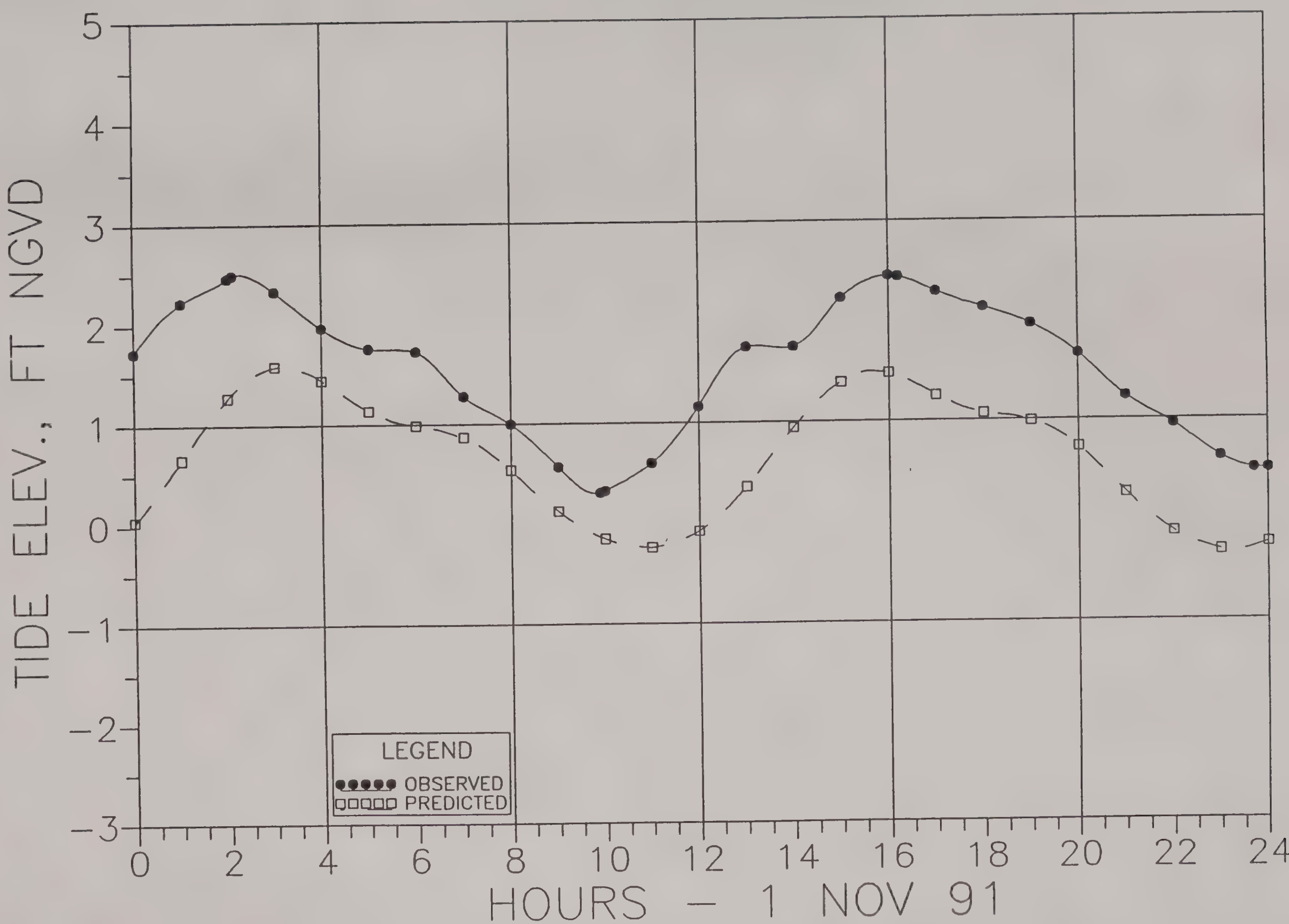


FIGURE 6 – PORTLAND, MAINE WINDS

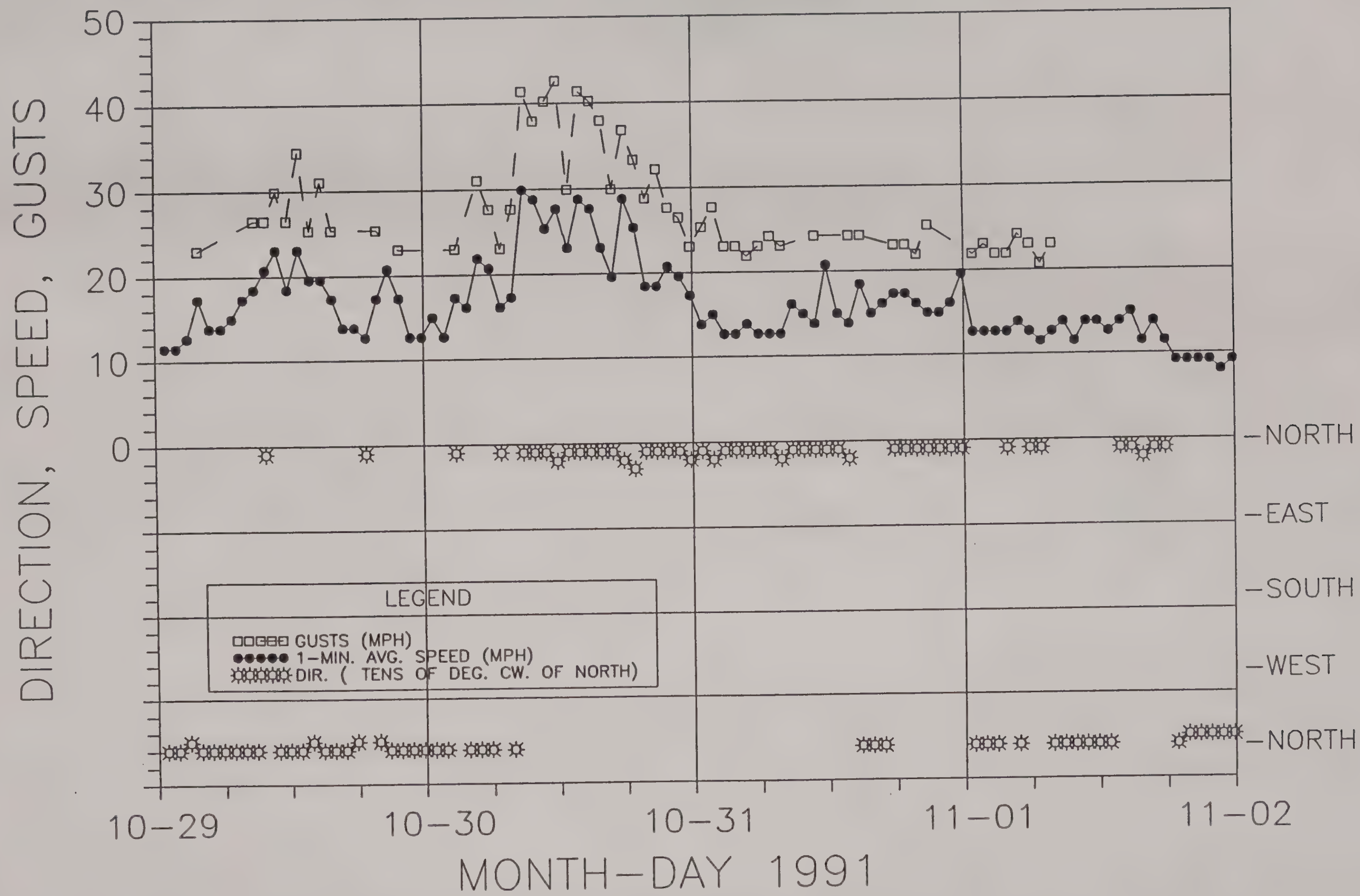


FIGURE 7 - BOSTON, MASS. WINDS

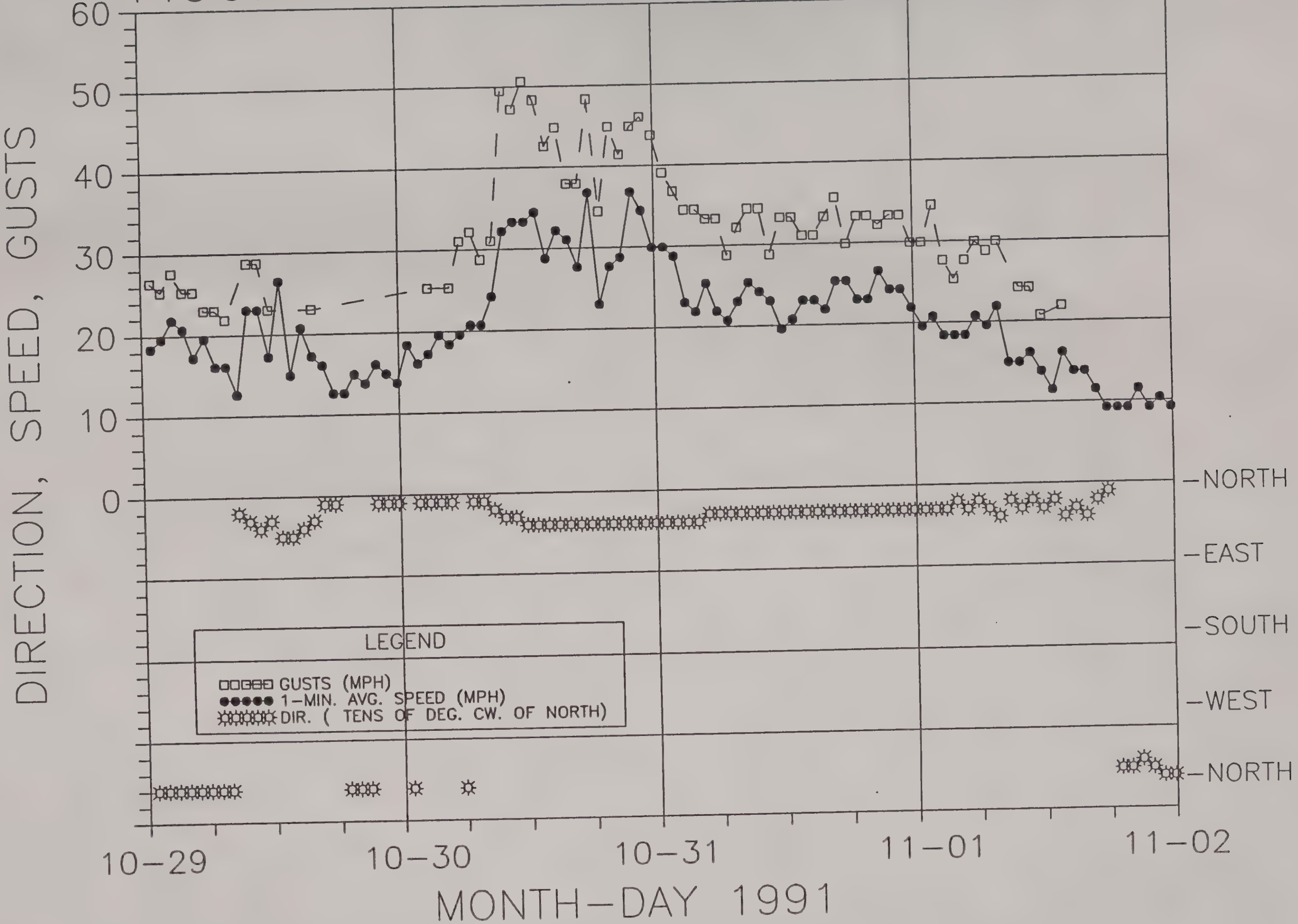


FIGURE 8 - CHATHAM, MASS. WINDS

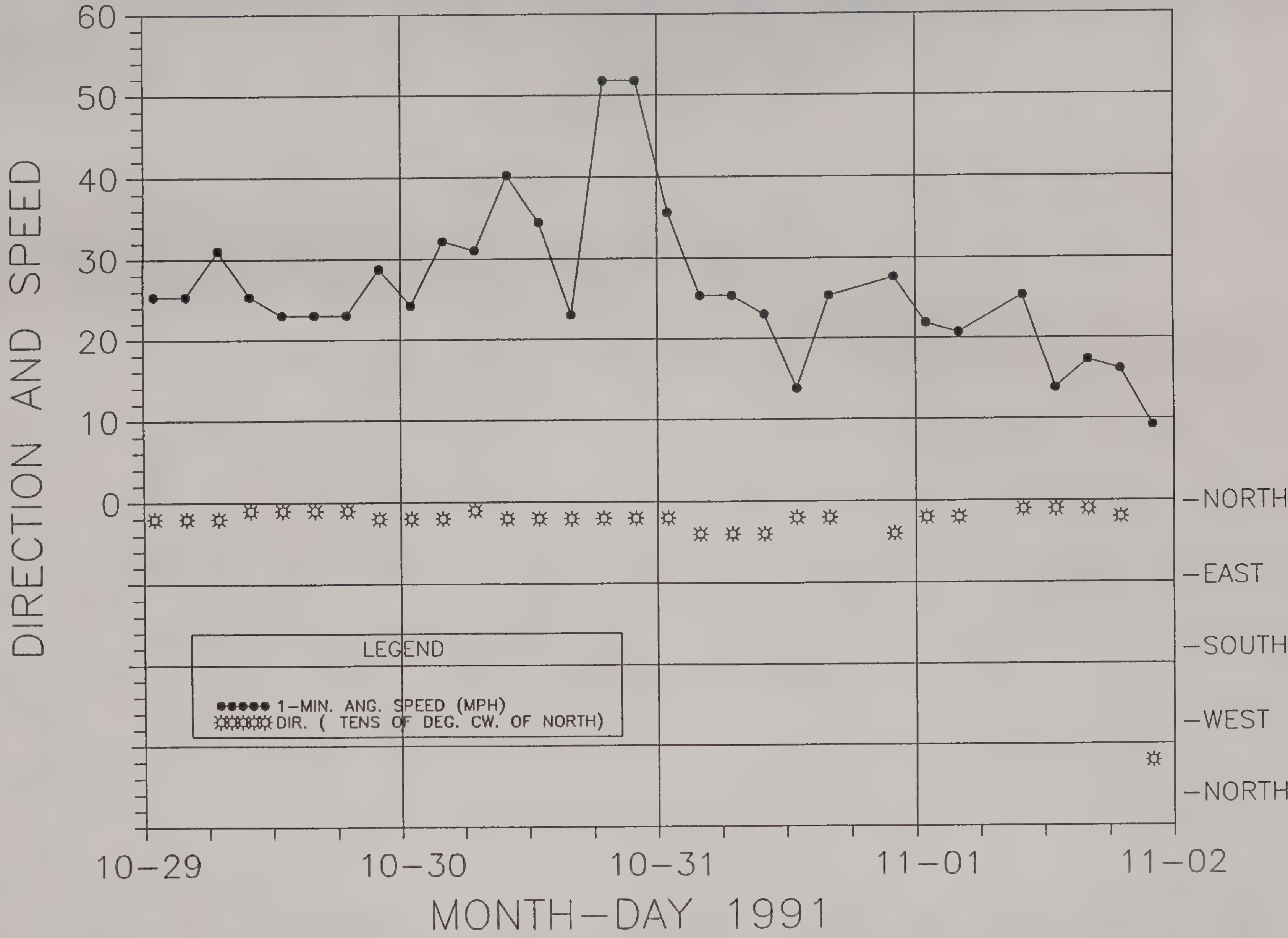


FIGURE 9 – NANTUCKET, MASS. WINDS

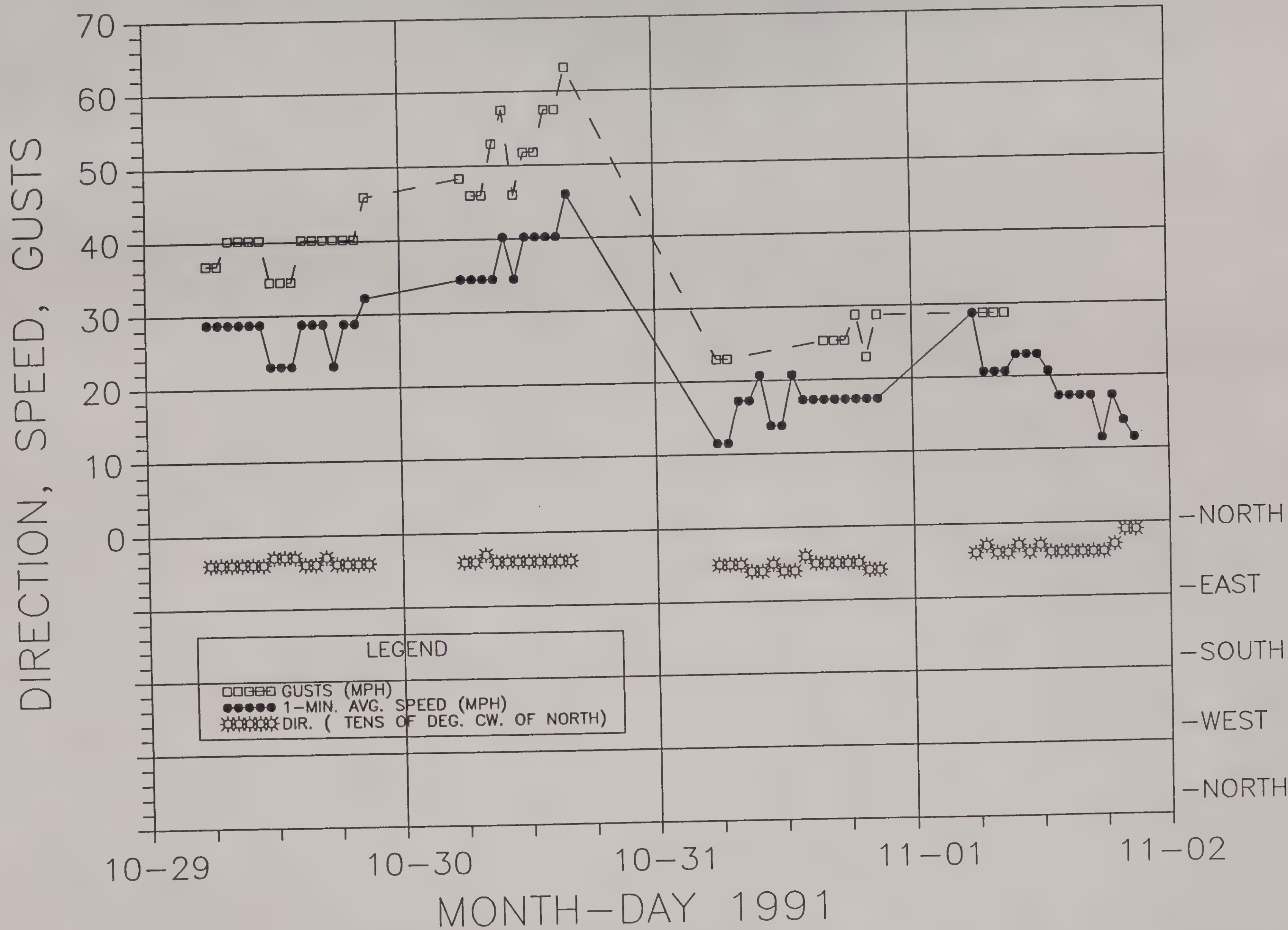


FIGURE 10 – PORTLAND, MAINE STATION PRESSURE

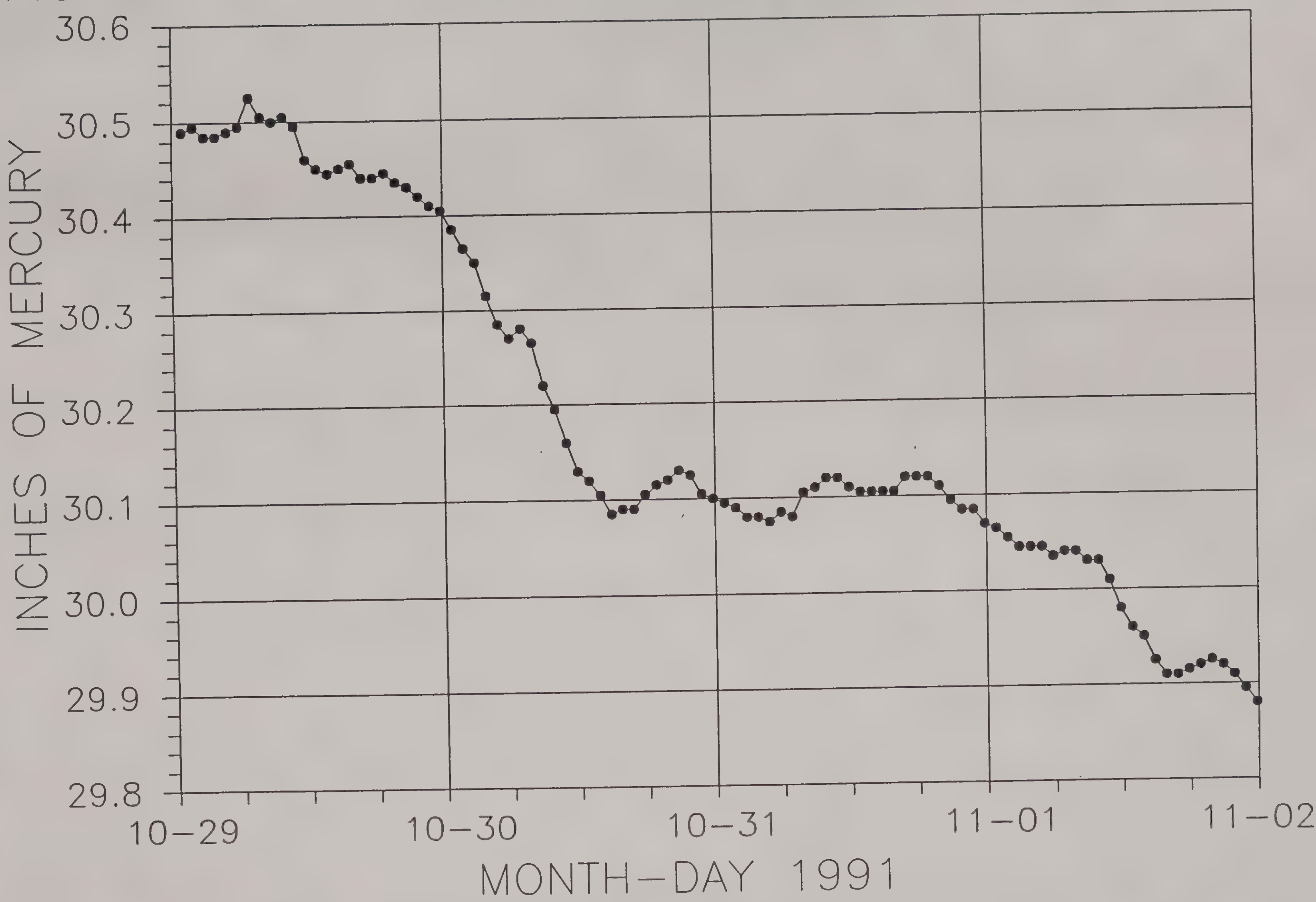


FIGURE 11 – BOSTON, MASS. STATION PRESSURE

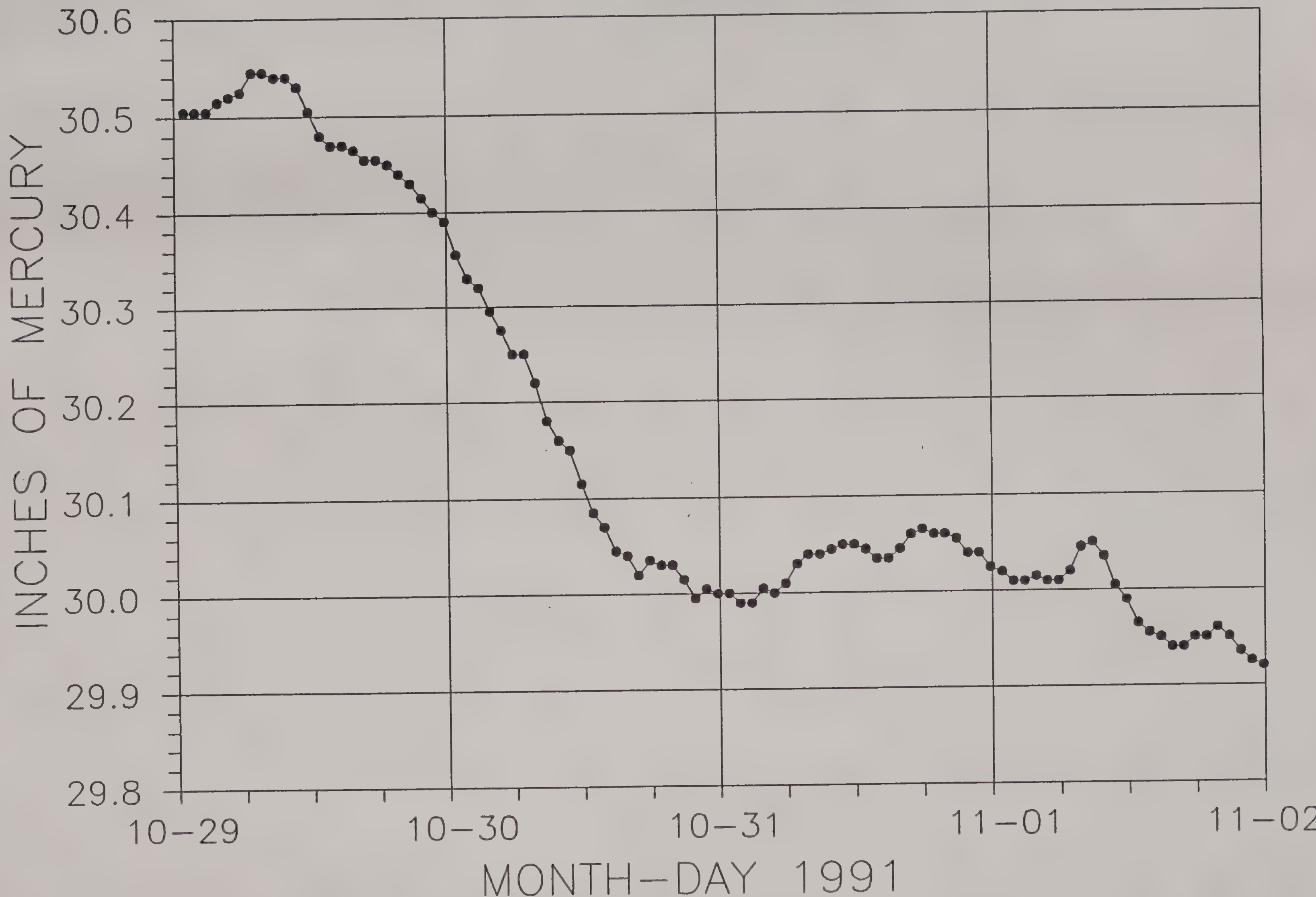


FIGURE 12 – CHATHAM, MASS. STATION PRESSURE

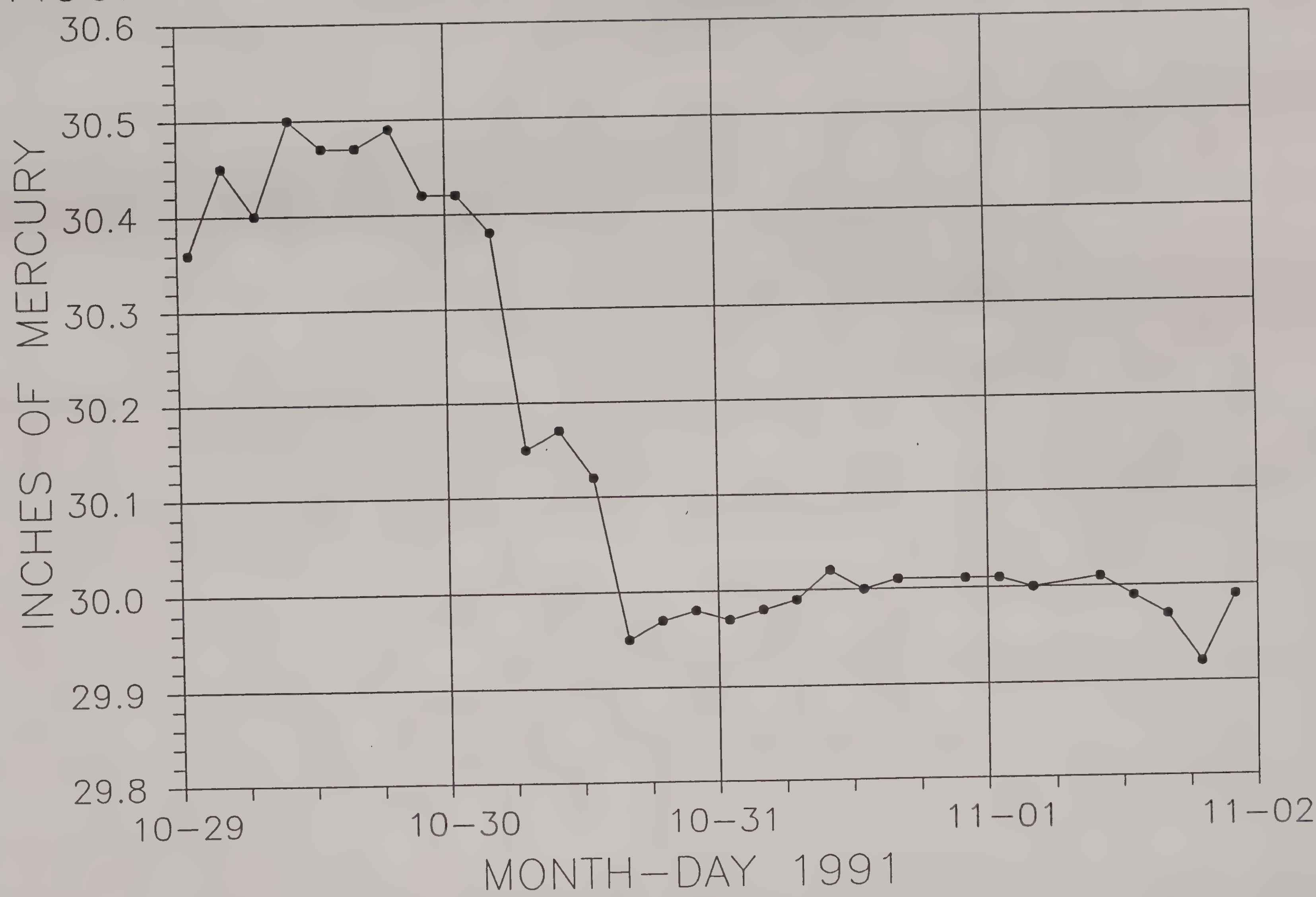
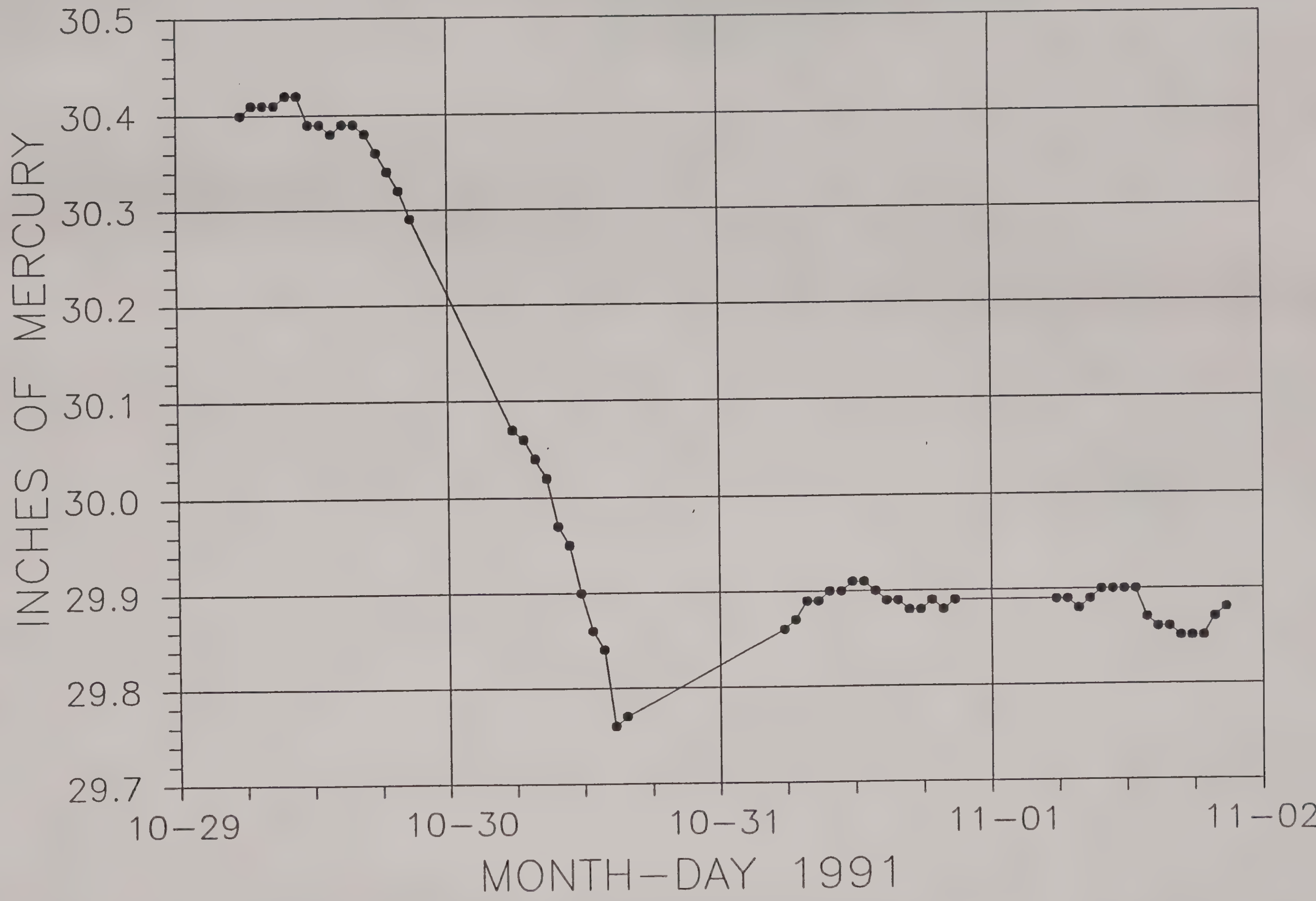
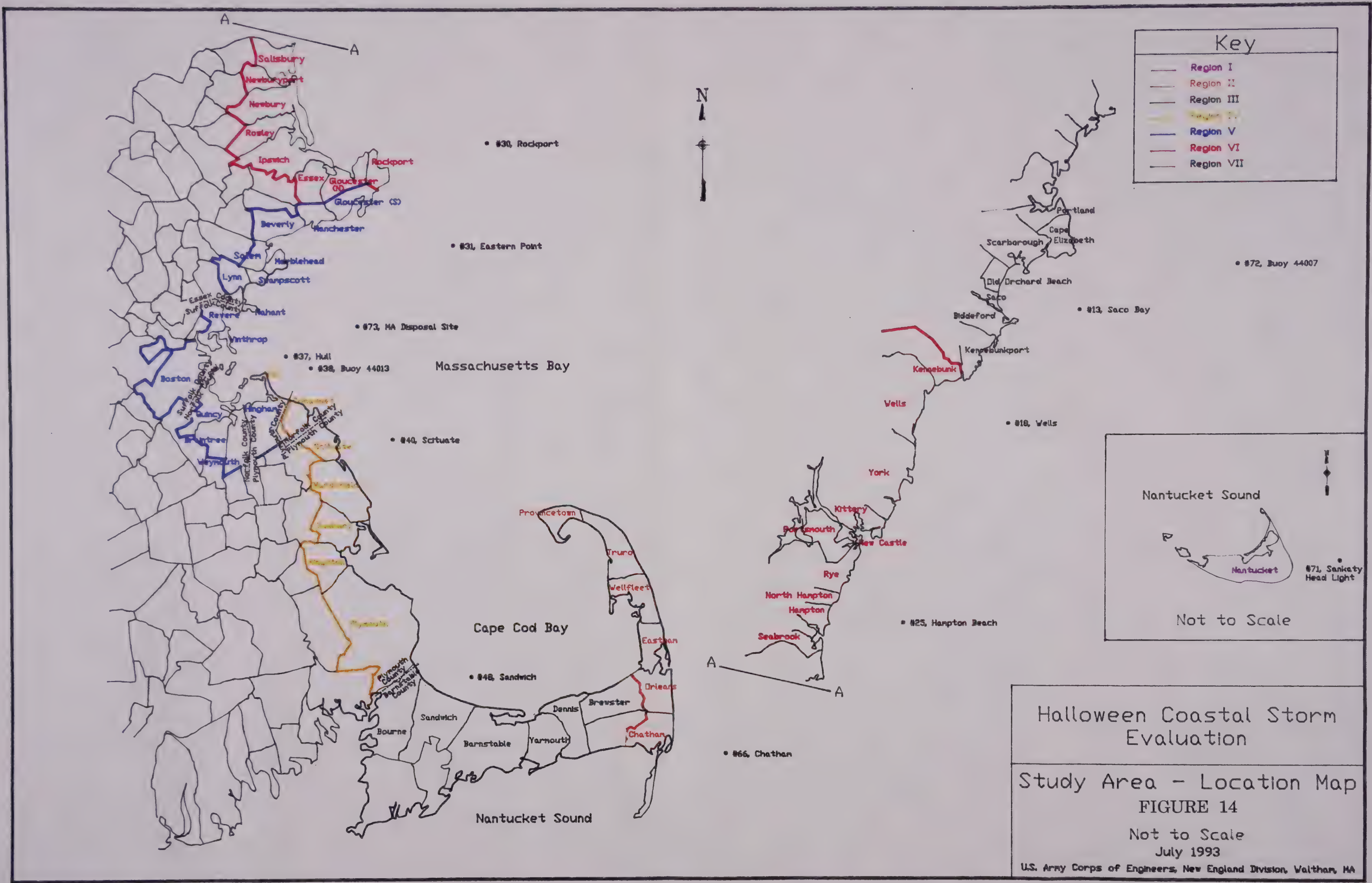


FIGURE 13 – NANTUCKET, MASS. STATION PRESSURE





Halloween Coastal Storm Evaluation

Study Area - Location Map

FIGURE 14

Not to Scale

July 1993

U.S. Army Corps of Engineers, New England Division, Waltham, MA

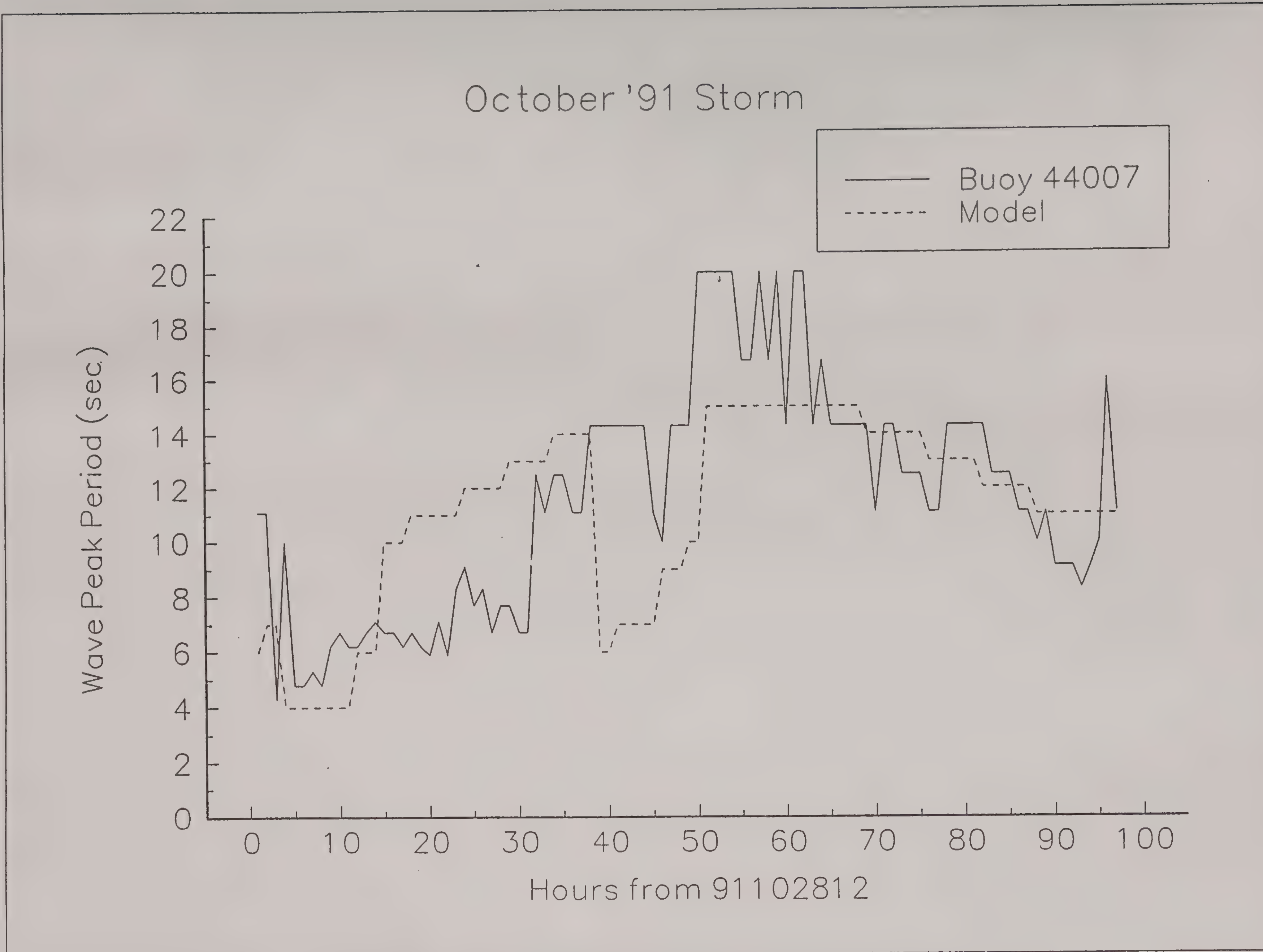


Figure 15 Measured and hindcast wave peak period during the Halloween storm of 1991 at NOAA buoy 44007 location.

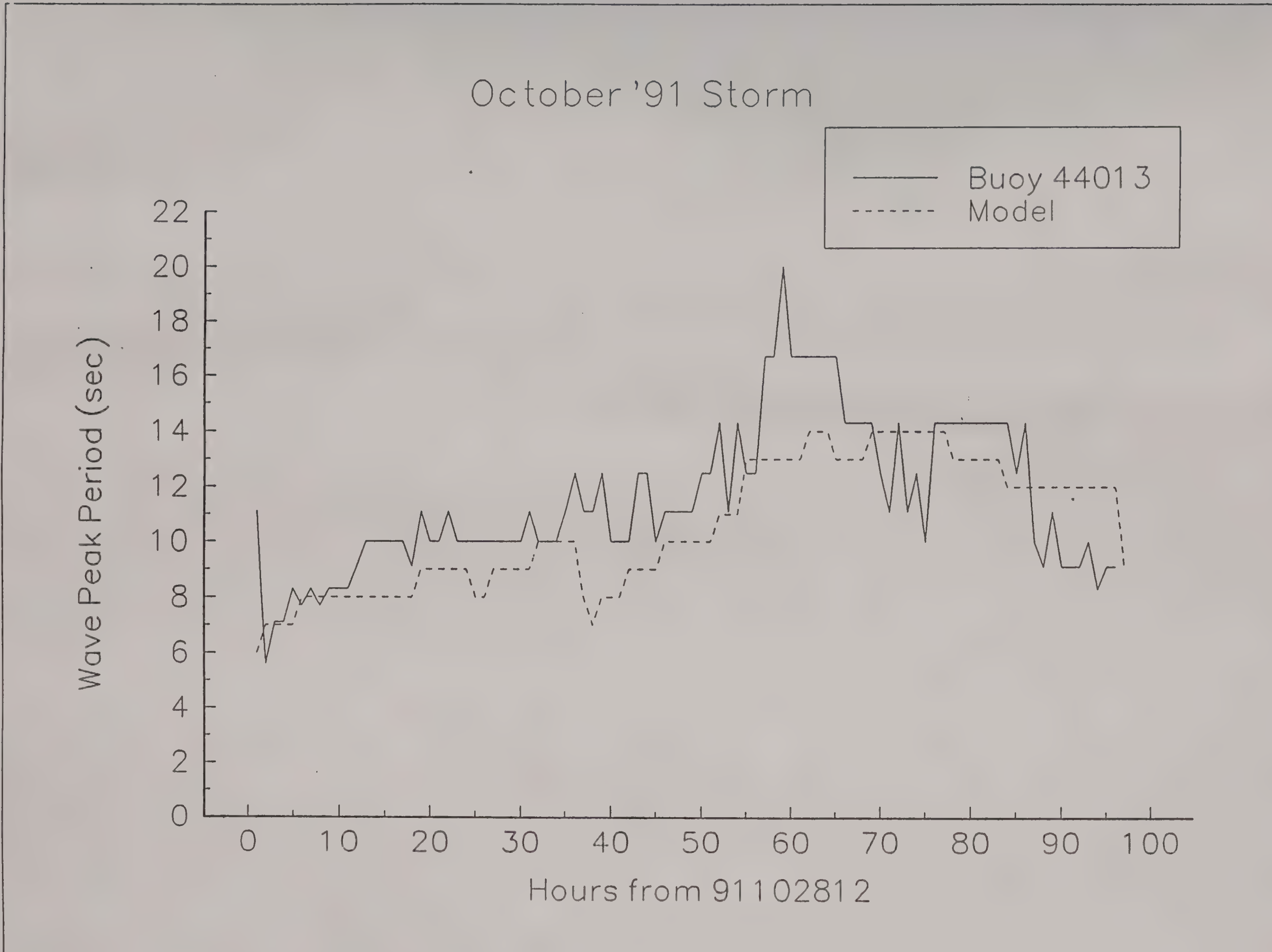


Figure 16 Measured and hindcast wave peak period during the Halloween storm of 1991 at NOAA buoy 44013 location.

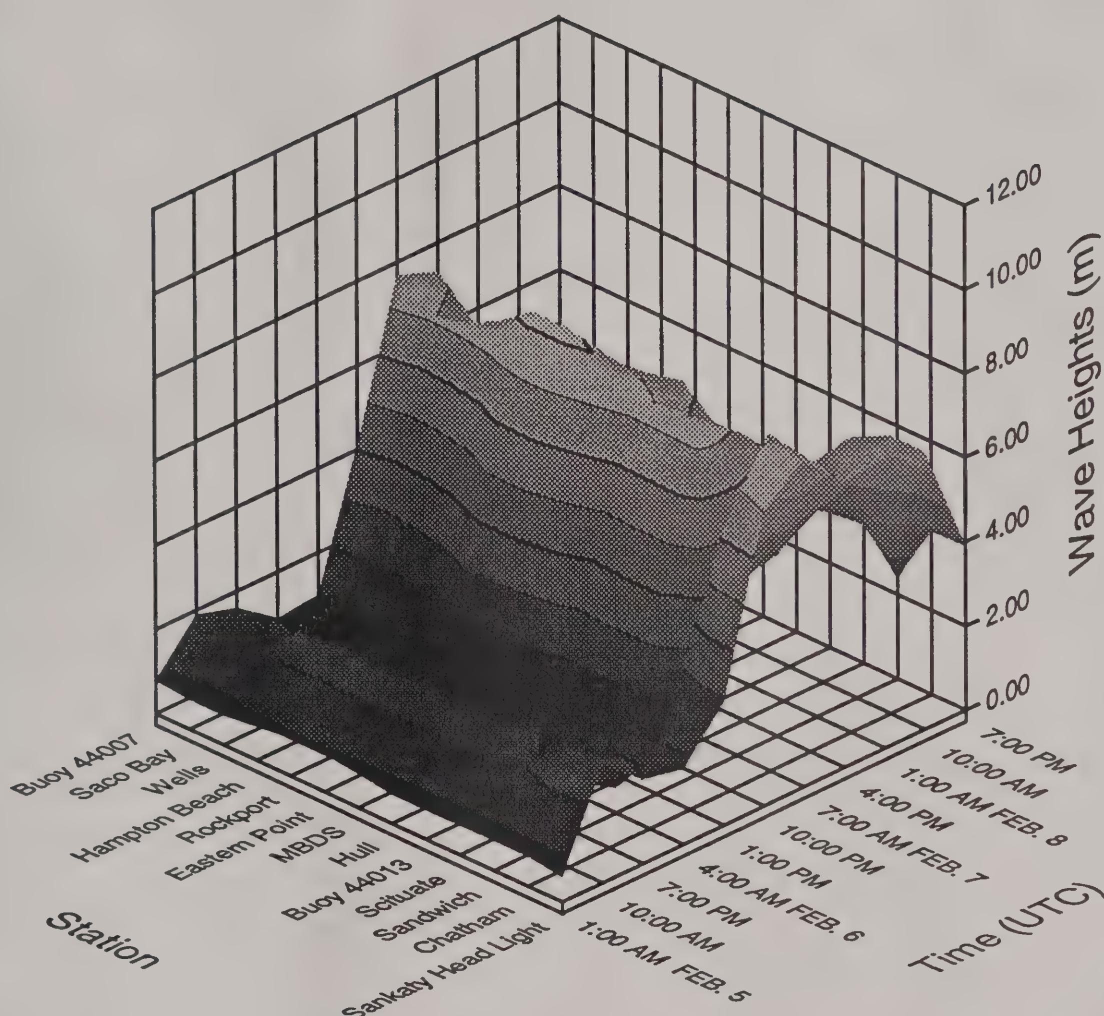


Figure 17

Blizzard of 1978 Wave Heights

New England Division

US Army Corps
of Engineers

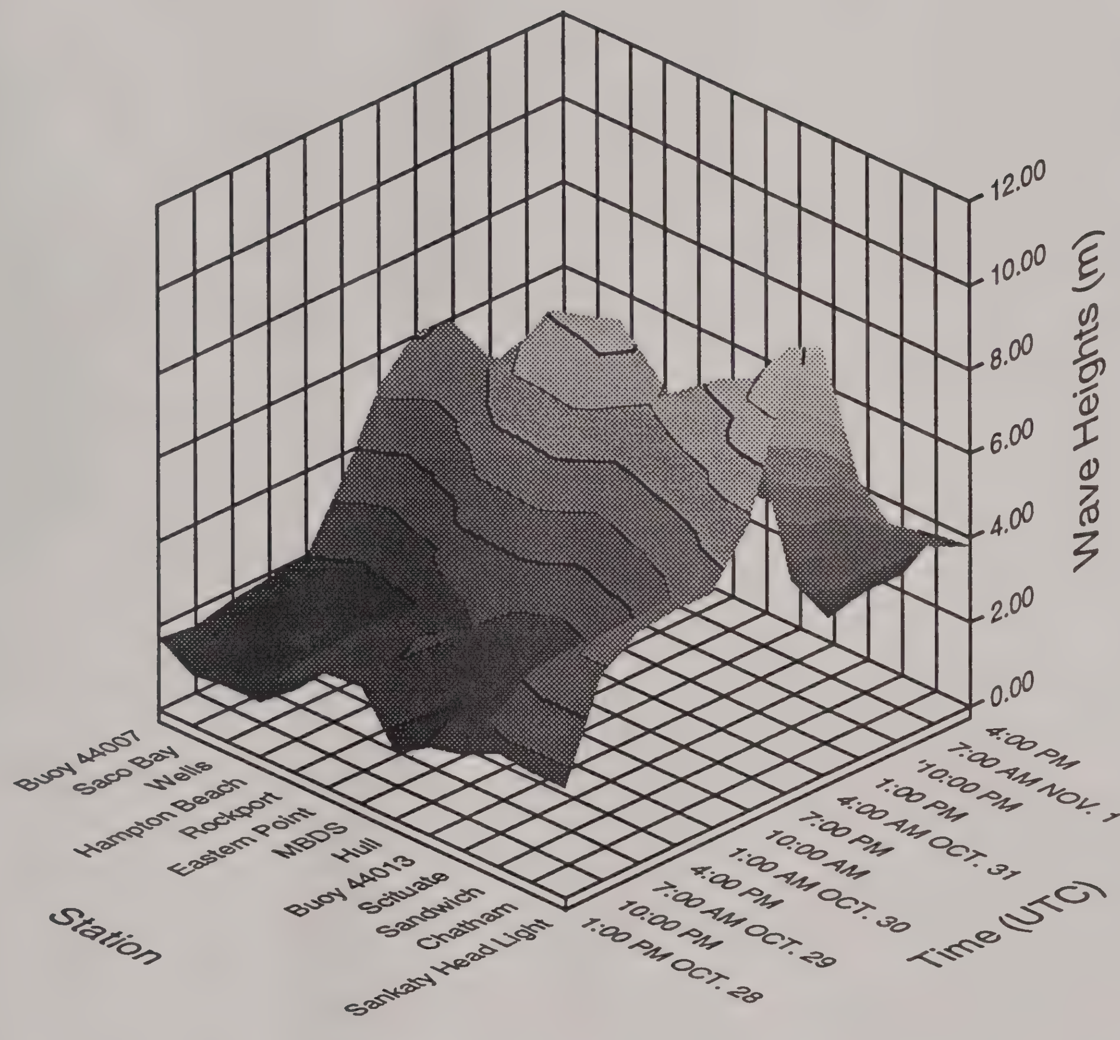


Figure 18

Halloween Storm of 1991 Wave Heights

New England Division

US Army Corps of Engineers

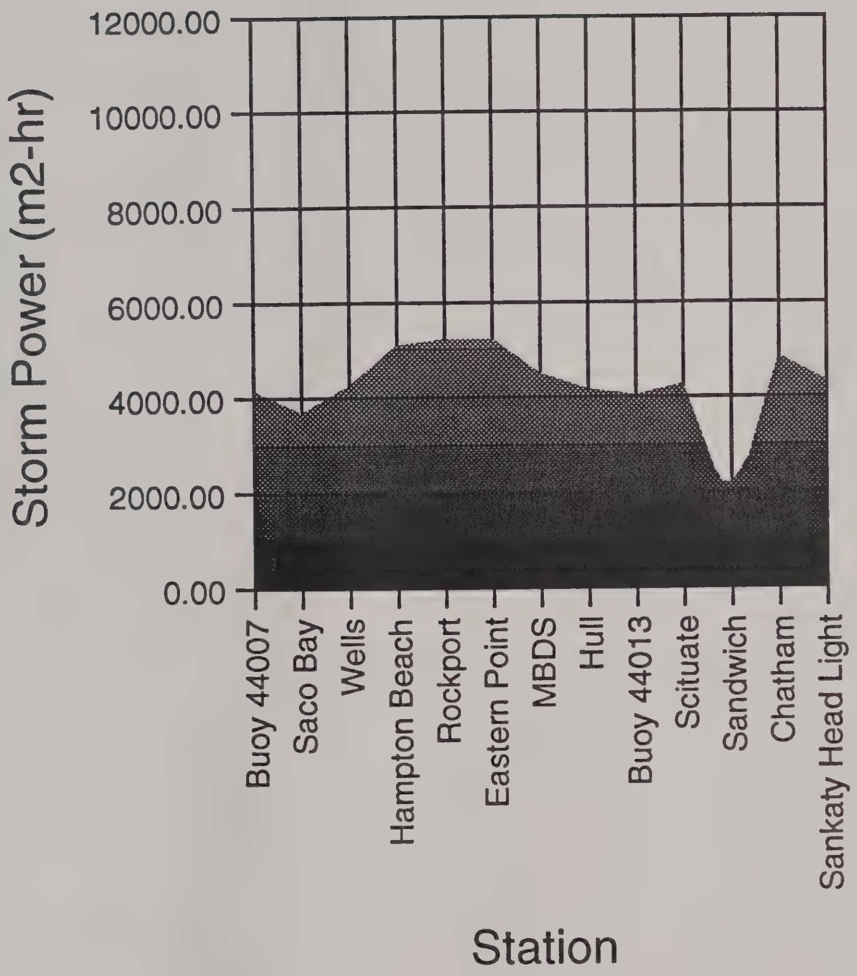


Figure 19

Blizzard of 1978 Storm Power

New England Division

US Army Corps of Engineers

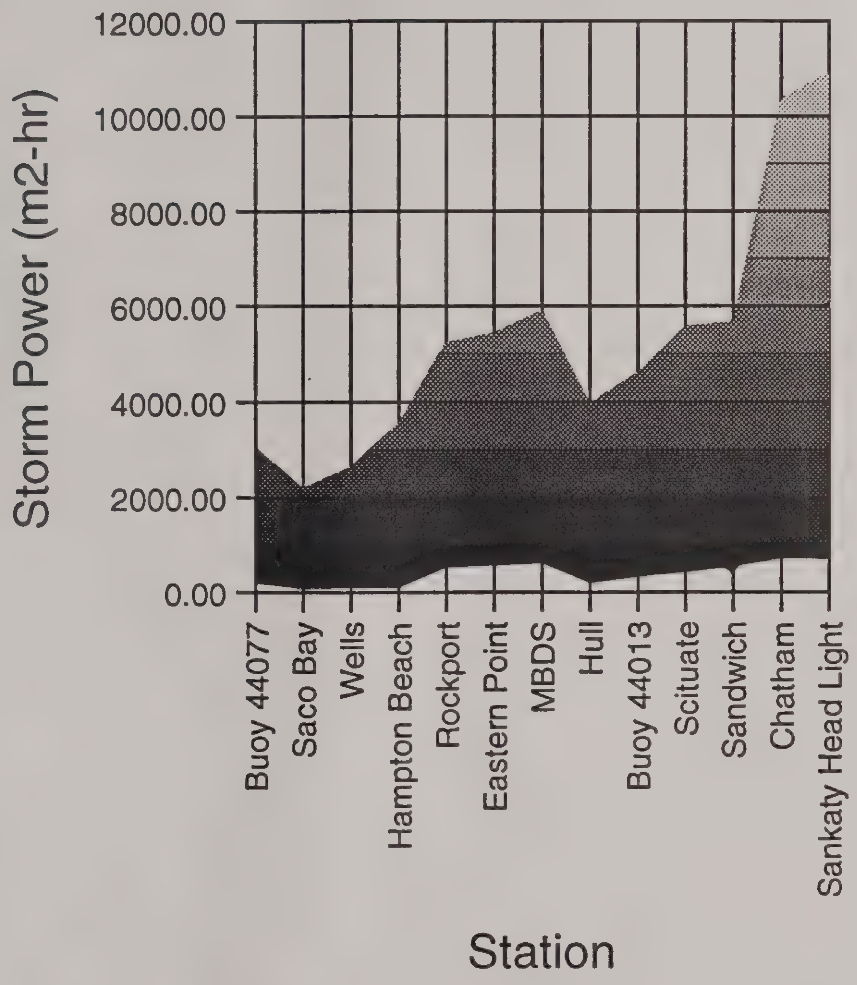


Figure 20

Halloween Storm of 1991 Storm Power

New England Division

US Army Corps of Engineers

APPENDIX A

HIGH WATER MARKS

1. Introduction

This appendix documents the elevation of approximately 200 high water marks obtained after the Halloween northeaster of October 1991. High water marks were obtained at various locations along the coast from Kennebunkport, Maine to Nantucket, Massachusetts. The complete documentation of high water marks from this event includes maps and photographs and is contained in a separate publication entitled "High Water Marks, Halloween Storm, October, 1991", October 1992, and is on file at the New England Division technical library.

The high water marks are meant to be an approximation of stillwater elevations, however, some are due to overtopping, wave runup, and ponding which are not representative of ocean stillwater levels. These are of interest to affected coastal communities, States, and other Federal agencies responsible for defining flood threats and evaluating mitigation measures. Information contained in this report provides historical documentation of the coastal flooding experienced along the New England coast from this event. High water marks and their corresponding elevations, referenced to either the National Geodetic Vertical Datum (NGVD), or Mean Lower Low Water (MLLW) are listed in Table 1 - Summary of High Water Marks. Only the elevations of the most reliable marks are presented in Table 1, however, the report contains photographs, descriptions, and location maps for all of the high water marks which were recovered. Those marks not considered reliable estimates of the stillwater level are still an important historical reference of flooding caused by the Halloween event. The elevations and locations of the more reliable high water marks are plotted for illustrative purposes only on Plates A-1 through A-3, Tidal Flood Profiles - New England Coastline, September 1988.

2. Data Collection

On November 2-6, 1991, the New England Division mobilized seven 2-person teams to mark and record the locations of identifiable stillwater elevations. Where possible, elevations were identified by debris lines that remained on inland areas or inside structures to avoid areas subjected to wave action. Local residents and public officials were often consulted at many locations for additional assistance in distinguishing high water marks.

Locations were marked with paint, stakes, tape and nails with pertinent information recorded on NED Standard Forms for High Water Mark Data collection. Photographs and sketches of the site were used to aid survey personnel in relocating the marks to determine the elevations. New England Division survey teams were deployed in December, 1991 to measure the high water mark elevations relative to the level of the ocean surface at the time of survey. The survey data was then adjusted using the predicted and actual tide elevations for the date of survey. This allowed the high water mark elevations to be converted to the National Geodetic Vertical Datum (NGVD). The datum used for Nantucket was Mean Lower Low Water (MLLW). A sample calculation of this method begins on page A-3.

The final elevations of the high water marks determined as a result of the survey are meant only as a general guide as to the severity of flooding at a particular location. There is a wide range of values associated with the data points representing the highwater mark elevations on the Tidal Flood Profiles. Numerous errors can be introduced when determining the high water mark elevations as a result of coastal storm events. Human error in locating the approximate level of stillwater in areas subjected to wave action is a predominant source of error. The location and elevation of high water marks is in many cases a subjective matter. Another possible source of error is the methodology used in determining the highwater mark elevations. The elevations were based on the approximate stillwater level of the ocean on the particular day the survey was accomplished, but this can be affected by wave action and weather conditions which may lead to errors.

3. Summary

The elevations of high water marks presented in this appendix were derived from actual observed tide elevations for the appropriate National Oceanic and Atmospheric Administration (NOAA) Station at the time and day of the survey. These marks are best used to indicate high water elevations over a region rather than at a specific site. The elevation of individual marks may not be accurate representations at a particular site. Trends in stillwater levels occurring in a particular region may exist when these marks are evaluated as a group rather than individually. Only those marks obtained from other storm events taken at locations in the proximity of the Halloween 1991 high water marks can be reasonably compared on an individual basis. For detailed information regarding specific high water mark locations, refer to the complete report "High Water Marks, Halloween Storm, October, 1991", October 1992, on file at the New England Division technical library.

The raw data of high water marks was reviewed for accuracy based on the observations of personnel in the field. Therefore, only those elevations found to be reasonably accurate are displayed in Table 1 and on the Tidal Flood Profiles - New England Coastline, September 1988. All elevations are in NGVD. The high water marks provide a database of information for referencing the effects of future storm events.

EXAMPLE DETERMINATION OF HIGH WATER MARK ELEVATION

For Site L1, Lynn, Massachusetts:

Step 1. After the high water level had been marked, a survey crew determined the elevation of the mark relative to the ocean surface for the date and time of their survey: Survey Date 12/2/91; Survey Time 3:32 PM (1532)

The survey recorded the water surface measured 18.25 feet and the high water mark 5.2 feet relative to the survey instrument. See Figure 1.

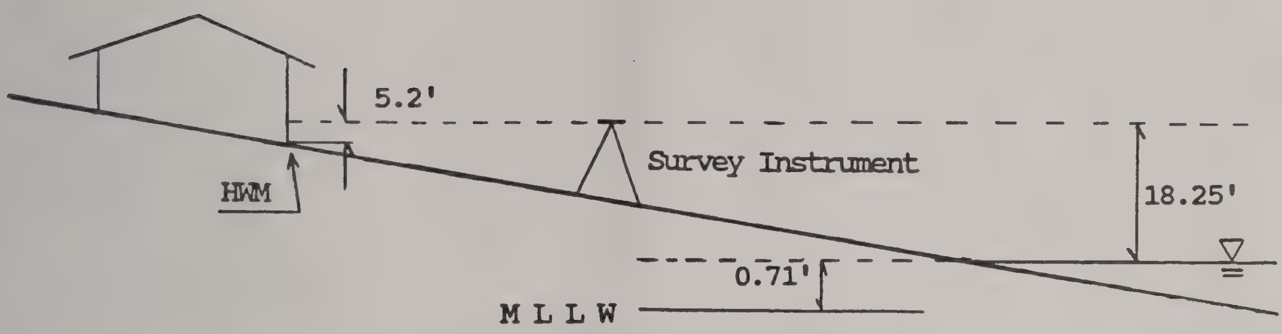


FIGURE 1

Step 2. High and Low tide times and elevations were obtained from National Oceanic and Atmospheric Administration, National Ocean Service (NOAA/NOS) tide gage stations at Portland, Boston, and Nantucket. The high and low tide times and elevations were then determined for the Sub-Station nearest the high water mark using appropriate difference factors contained in "Tide Tables 1992 - East Coast of North and South America, Including Greenland, (NOAA)". The tide characteristics at the high water mark locations were assumed to be the same as at the nearest Sub-Station.

Tidal difference factors for Lynn Harbor are:

Time (min)		Height (ft)	
High Water	Low Water	High Water	Low Water
+10	+06	*0.96	*.096

Step 3. Apply the difference factors to the Boston tide data to estimate tidal information for Lynn on December 2, 1991:

High		Low	
Time (min)	Height (ft)	Time (min)	Height (ft)
1228	9.187	858	-0.182

Step 4. Determine the linear time fraction of the tidal cycle to the time of survey:

The time of survey is 1532 (932 minutes). The time of survey must fall between the time of high and low tides.

High Tide Time - Low Tide Time = 1228 - 858 = 370
(Survey Time - Low Tide Time)/ 370 = .200

Time Fraction = .200

Step 5. Determine the fractional change in tide height at the time of survey. Assume that variations in tide heights between low and high tides follows a sinusoidal relationship:

Use [1 - COS(PI x Time Fraction)] x 0.5
Note: The Linear Time Fraction should be in radians.

[1 - COS(PI x .200 radians)] x 0.5 = 0.096

Height Fraction = 0.096

Step 6. Determine the height of water at time of survey relative to MLLW.

Ht. = Low Tide + [Sinusoidal Height Fraction x (HT - LT heights)]

-.1824 + [0.096 x (9.187 -(-.1824))] = .71 Height of water surface (MLLW)

Step 7. Convert high water mark elevation to NGVD:
Refer to Figure 1.

Height of water mark (MLLW) at time of survey:
.71 + 18.25 - 5.20 = 13.76 MLLW

Convert to NGVD:
13.76 MLLW - 0.34 (MLLW to MLW) - 4.5 (MLW to NGVD) = <u>8.92 NGVD</u>

Note: MLLW: Mean Lower Low Water
MLW: Mean Low Water
NGVD: National Geodetic Vertical Datum

TABLE 1 - SUMMARY OF HIGH WATER MARKS

SITE NO.	STATE/ TOWN	HIGH WATER MARKS ELEVATION (NGVD)
	MAINE	
E1	ELIOT	8.1
K1	KITTERY	----
K2	KITTERY	9.1
K3	KITTERY	9.2
K4	KITTERY	----
K5	KITTERY	9.4
S1	SEABURY	----
Y1	YORK HARBOR	----
Y2	YORK HARBOR	----
CN1	CAPE NEDDICK	----
CN2	CAPE NEDDICK	10.8
CN3	CAPE NEDDICK	----
O1	OGUNQUIT	----
W1	WELLS	----
W2	WELLS	----
W3	WELLS	9.2
W4	WELLS	----
W5	WELLS	----
W6	WELLS	----
KB1	KENNEBUNK	11.3
KB2	KENNEBUNK	----
KB3	KENNEBUNK	10.8
KP1	KENNEBUNKPORT	----
KP2	KENNEBUNKPORT	9.5
KP3	KENNEBUNKPORT	9.8
KP4	KENNEBUNKPORT	11.9
KP5	KENNEBUNKPORT	10.2
KP6	KENNEBUNKPORT	7.9
KP7	KENNEBUNKPORT	11.0
	NEW HAMPSHIRE	
SB1	SEABROOK	----
SB2	SEABROOK	10.2

TABLE 1 - continued

SITE NO.	STATE/ TOWN	HIGH WATER MARKS ELEVATION (NGVD)
	MASSACHUSETTS	
S1	SALISBURY	8.7
S2	SALISBURY	9.9
S3	SALISBURY	6.8
N1	NEWBURYPORT	10.4
N2	NEWBURYPORT	10.8
N3	NEWBURYPORT	----
N4	NEWBURYPORT	8.1
N5	NEWBURYPORT	----
N6	NEWBURYPORT	9.4
N7	NEWBURYPORT	----
N8	NEWBURYPORT	8.3
N9	NEWBURY	9.5
N10	NEWBURY	----
RY1	ROWLEY	----
RY2	ROWLEY	9.9
I1	IPSWICH	----
I2	IPSWICH	11.3
I3	IPSWICH	9.9
I4	IPSWICH	----
I5	IPSWICH	10.4
I6	IPSWICH	11.1
E1	ESSEX	11.4
E2	ESSEX	11.7
E3	ESSEX	9.6
G1	GLOUCESTER	----
G2	GLOUCESTER	11.4
G3	GLOUCESTER	11.2
G4	GLOUCESTER	10.9
G5	GLOUCESTER	10.6
G6	GLOUCESTER	----
G7	GLOUCESTER	11.7
G8	GLOUCESTER	9.9
G9	GLOUCESTER	----
G10	GLOUCESTER	8.6
G11	GLOUCESTER	7.2
R1	ROCKPORT	10.5
R2	ROCKPORT	9.9
R3	ROCKPORT	9.0
MN1	MANCHESTER	----
MN2	MANCHESTER	----
MN3	MANCHESTER	10.2
MN4	MANCHESTER	----
BV1	BEVERLY	----
BV2	BEVERLY	----
DN1	DANVERS	8.5
DN2	DANVERS	8.6
SL1	SALEM	8.8

TABLE 1 - continued

SITE NO.	STATE/ TOWN	HIGH WATER MARKS ELEVATION (NGVD)
	MASSACHUSETTS	
SL2	SALEM	11.2
SL3	SALEM	11.2
MB1	MARBLEHEAD	12.7
MB2	MARBLEHEAD	——
MB3	MARBLEHEAD	11.4
SW1	SWAMPSCOTT	11.1
SW2	SWAMPSCOTT	10.8
SW3	SWAMPSCOTT	——
SW4	SWAMPSCOTT	11.8
SW5	SWAMPSCOTT	12.9
L1	LYNN	8.9
L2	LYNN	9.0
L3	LYNN	——
L4	LYNN	——
L5	LYNN	——
L6	LYNN	——
L7	LYNN	8.4
L8	LYNN	8.4
L9	LYNN	——
NH1	NAHANT	——
SG1	SAUGUS	——
SG2	SAUGUS	——
SG3	SAUGUS	——
RV1	REVERE	10.1
RV2	REVERE	——
RV3	REVERE	9.4
RV4	REVERE	——
RV5	REVERE	10.2
RV6	REVERE	——
RV7	REVERE	——
RV8	REVERE	9.2
RV9	REVERE	8.4
RV10	REVERE	8.4
RV11	REVERE	8.3
RV12	REVERE	——
RV13	REVERE	9.6
RV14	REVERE	7.8
RV15	REVERE	7.4
RV16	REVERE	8.3
RV17	REVERE	——
RV18	REVERE	——
RV19	REVERE	——
RV20	REVERE	——
RV21	REVERE	——
W1	WINTHROP	——
W2	WINTHROP	10.1

TABLE 1 - continued

SITE NO.	STATE/ TOWN	HIGH WATER MARKS ELEVATION (NGVD)
	MASSACHUSETTS	
H1	HULL	12.9
H2	HULL	——
H3	HULL	——
H4	HULL	10.4
H5	HULL	——
C1	COHASSET	——
C2	COHASSET	——
C3	COHASSET	9.5
S1	SCITUATE	9.6
S2	SCITUATE	11.9
S3	SCITUATE	14.4
S4	SCITUATE	——
S5	SCITUATE	13.3
S6	SCITUATE	——
S7	SCITUATE	——
S8	SCITUATE	——
M1	MARSHFIELD	12.6
M2	MARSHFIELD	——
M3	MARSHFIELD	——
M4	MARSHFIELD	——
D1	DUXBURY	——
D2	DUXBURY	12.7
D3	DUXBURY	11.4
D4	DUXBURY	11.1
D5	DUXBURY	——
K1	KINGSTON	——
P1	PLYMOUTH	——
P2	PLYMOUTH	11.8
P3	PLYMOUTH	11.9
P4	PLYMOUTH	——
P5	PLYMOUTH	——
P6	PLYMOUTH	12.8
P7	PLYMOUTH	——
P8	PLYMOUTH	——
P9	PLYMOUTH	——
SA1	SANDWICH	11.4
CH1	CHATHAM	——
CH2	CHATHAM	4.1
CH3	CHATHAM	3.0
CH4	CHATHAM	7.5
CH5	CHATHAM	——
OR1	ORLEANS	12.4
OR2	ORLEANS	——
OR3	ORLEANS	——
OR4	ORLEANS	9.5
E1	EASTHAM	10.6

TABLE 1 - continued

SITE NO.	STATE/ TOWN	HIGH WATER MARKS ELEVATION (NGVD)
	MASSACHUSETTS	
E2	EASTHAM	----
E3	EASTHAM	10.8
T1	TRURO	7.6
PR1	PROVINCETOWN	12.8

TABLE 1 - continued

SITE NO.	STATE/ TOWN	HIGH WATER MARKS ELEVATION (MLLW)
	MASSACHUSETTS	
1	MADAKET, NANT.	7.1
2	MADAKET, NANT.	8.3
3	MADAKET, NANT.	——
4	NANTUCKET	9.5
5	NANTUCKET	8.6
6	NANTUCKET	8.5
7	NANTUCKET	8.4
8	NANTUCKET	8.2
9	NANTUCKET	7.9
10	NANTUCKET	——
11	NANTUCKET	8.3
12	NANTUCKET	8.4
13	NANTUCKET	——
14	NANTUCKET	7.9
15	NANTUCKET	9.8
16	NANTUCKET	9.3
17	WAUWINET, NANT.	7.3
18	SHAWKEMO, NANT.	8.3
19	SQUAM, NANT.	——
20	QUIDNET, NANT.	——
21	SIASCONSET, NA.	——

Note: Those points whose elevations have not been recorded were not accurate representations of the stillwater elevation at that location.

CORPS OF ENGINEERS

U. S. ARMY

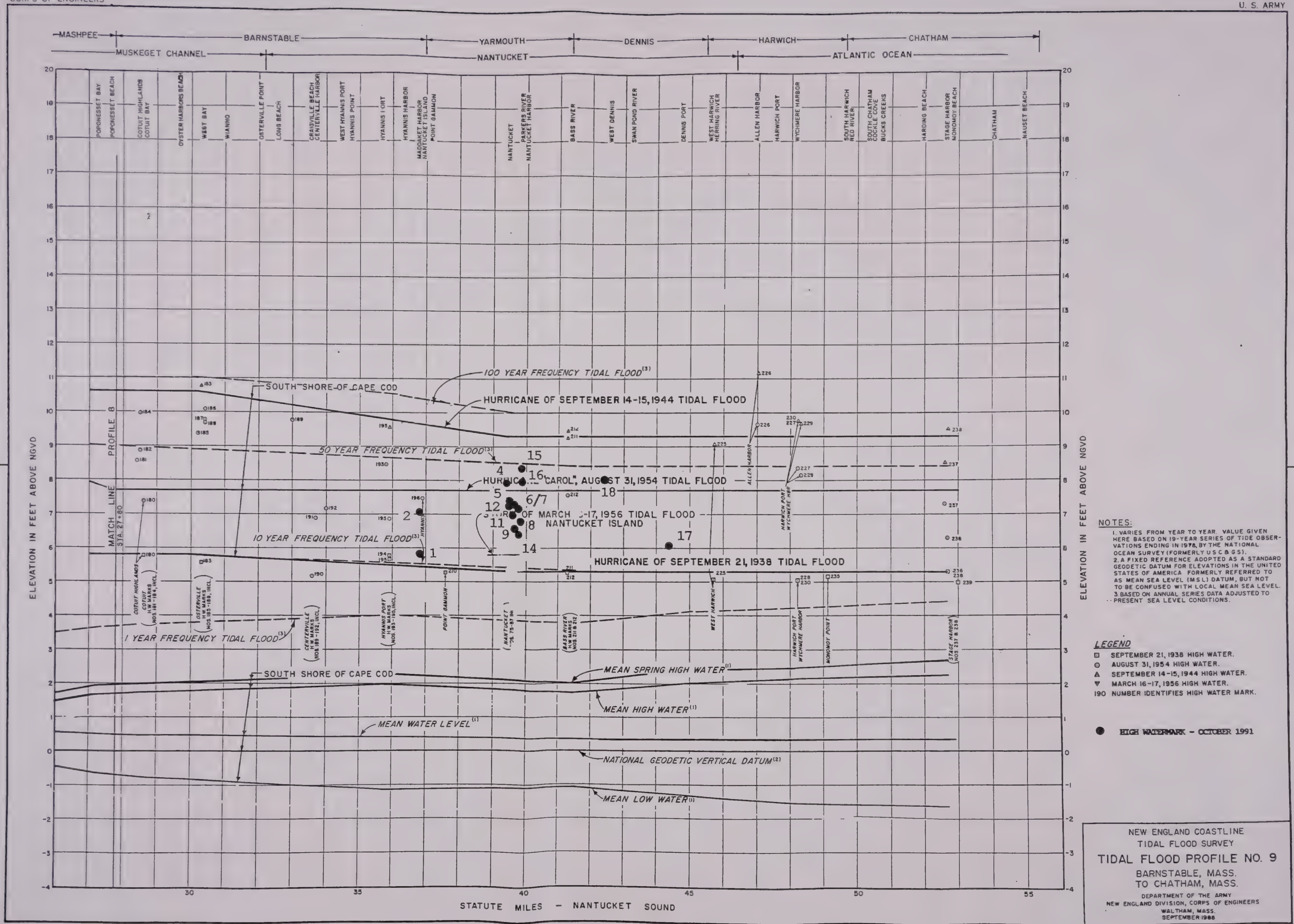


Plate A-1

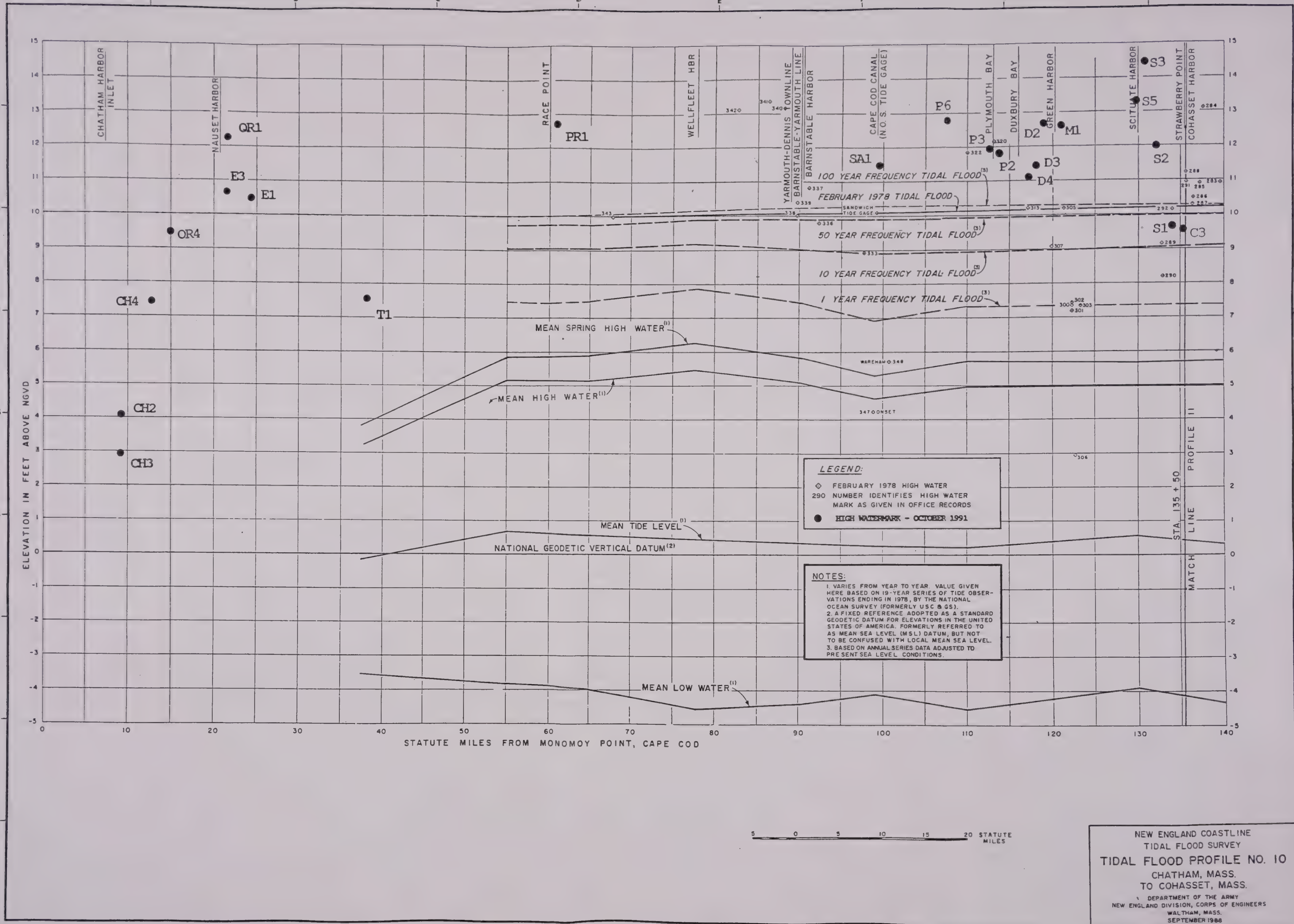
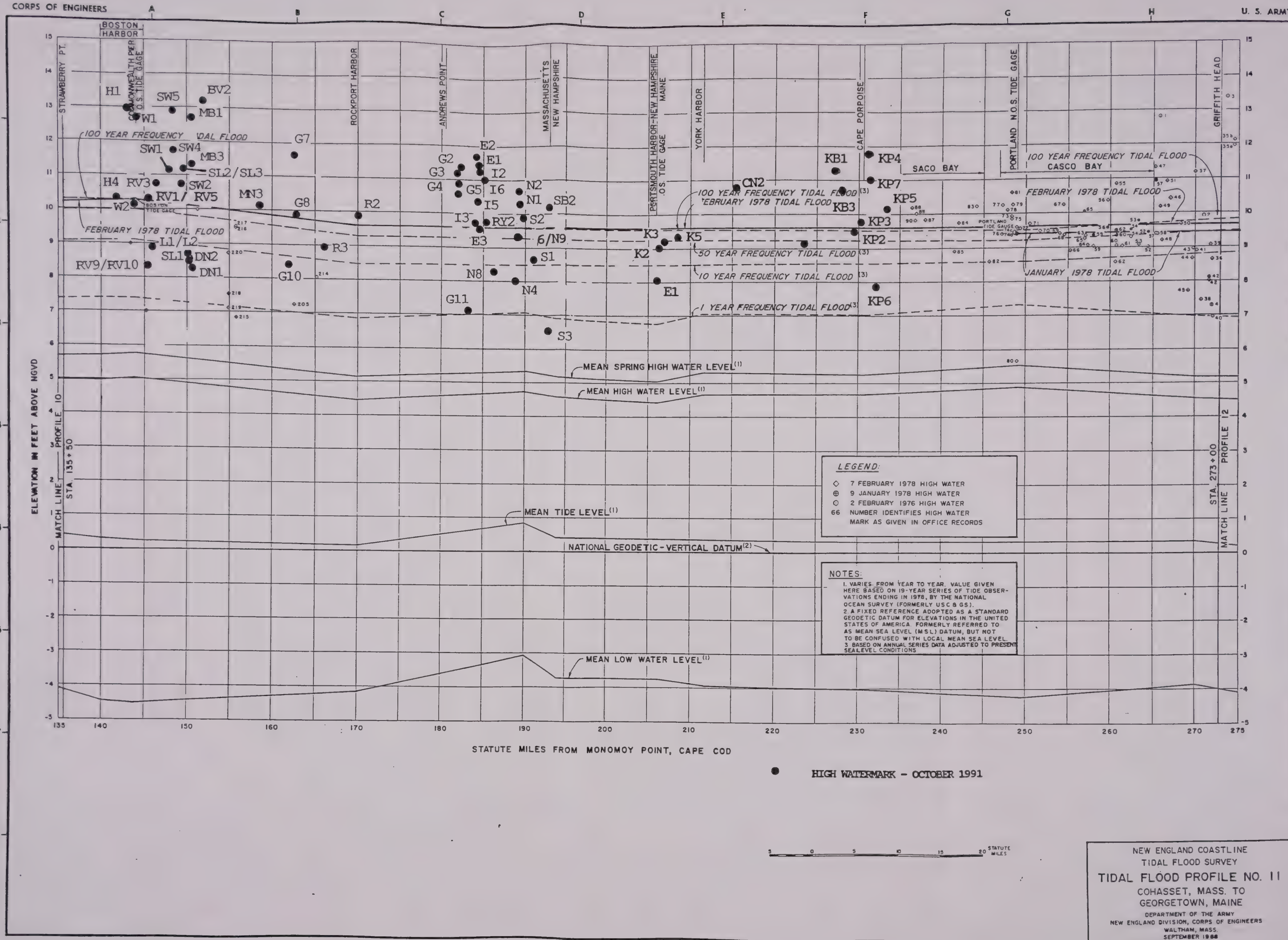

CORPS OF ENGINEERS
U. S. ARMY
CHATHAM HARBOR INLET
NAUSET HARBOR
RACE POINT
WELLFLEET HBR
YARMOUTH-DENNIS TOWNLINE
BARNSTABLE-YARMOUTH LINE
BARNSTABLE HARBOR
CAPE COD CANAL (N.O.S. TIDE GAGE)
PLYMOUTH BAY
DUXBURY BAY
GREEN HARBOR
SCITUATE HARBOR
STRAWBERRY POINT
COHASSET HARBOR
100 YEAR FREQUENCY TIDAL FLOOD(3)
FEBRUARY 1978 TIDAL FLOOD
50 YEAR FREQUENCY TIDAL FLOOD(3)
10 YEAR FREQUENCY TIDAL FLOOD(3)
1 YEAR FREQUENCY TIDAL FLOOD(3)
MEAN SPRING HIGH WATER(1)
MEAN HIGH WATER(1)
MEAN TIDE LEVEL(1)
NATIONAL GEODETIC VERTICAL DATUM(2)
MEAN LOW WATER(1)
ELEVATION IN FEET ABOVE NGVD
STATUTE MILES FROM MONOMOY POINT, CAPE COD
STA. 135 + 50
MATCH LINE PROFILE 11
LEGEND:
FEBRUARY 1978 HIGH WATER
290 NUMBER IDENTIFIES HIGH WATER MARK AS GIVEN IN OFFICE RECORDS
HIGH WATERMARK - OCTOBER 1991
NOTES:
1. VARIES FROM YEAR TO YEAR. VALUE GIVEN HERE BASED ON 19-YEAR SERIES OF TIDE OBSERVATIONS ENDING IN 1978, BY THE NATIONAL OCEAN SURVEY (FORMERLY USC & GS).
2. A FIXED REFERENCE ADOPTED AS A STANDARD GEODETIC DATUM FOR ELEVATIONS IN THE UNITED STATES OF AMERICA. FORMERLY REFERRED TO AS MEAN SEA LEVEL (M.S.L.) DATUM, BUT NOT TO BE CONFUSED WITH LOCAL MEAN SEA LEVEL.
3. BASED ON ANNUAL SERIES DATA ADJUSTED TO PRESENT SEA LEVEL CONDITIONS.
CH4
CH2
CH3
OR4
OR1
E3
E1
T1
PR1
SA1
P6
P3
P2
D2
D3
D4
M1
S3
S5
S2
S1
C3
SANDWICH TIDE GAGE
WAREHAM
ONSET
STATUTE MILES
NEW ENGLAND COASTLINE
TIDAL FLOOD SURVEY
TIDAL FLOOD PROFILE NO. 10
CHATHAM, MASS.
TO COHASSET, MASS.
DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION, CORPS OF ENGINEERS
WALTHAM, MASS.
SEPTEMBER 1988

Plate A-2


CORPS OF ENGINEERS
U. S. ARMY
BOSTON HARBOR
STRAWBERRY PT.
COMMONWEALTH PIER U.S. TIDE GAGE
ROCKPORT HARBOR
ANDREWS POINT
MASSACHUSETTS NEW HAMPSHIRE
PORTSMOUTH HARBOR-NEW HAMPSHIRE MAINE
U.S. TIDE GAGE
YORK HARBOR
CAPE PORPOISE
PORTLAND N.O.S. TIDE GAGE
GRIFFITH HEAD
SACO BAY
CASCO BAY
100 YEAR FREQUENCY TIDAL FLOOD
FEBRUARY 1978 TIDAL FLOOD
50 YEAR FREQUENCY TIDAL FLOOD (3)
10 YEAR FREQUENCY TIDAL FLOOD (3)
1 YEAR FREQUENCY TIDAL FLOOD (3)
JANUARY 1978 TIDAL FLOOD
MEAN SPRING HIGH WATER LEVEL (1)
MEAN HIGH WATER LEVEL (1)
MEAN TIDE LEVEL (1)
NATIONAL GEODETIC - VERTICAL DATUM (2)
MEAN LOW WATER LEVEL (1)
ELEVATION IN FEET ABOVE NGVD
MATCH LINE - PROFILE 10
STA. 135+50
MATCH LINE - PROFILE 12
STA. 273+00
STATUTE MILES FROM MONOMOY POINT, CAPE COD
LEGEND:
◇ 7 FEBRUARY 1978 HIGH WATER
⊕ 9 JANUARY 1978 HIGH WATER
○ 2 FEBRUARY 1976 HIGH WATER
66 NUMBER IDENTIFIES HIGH WATER MARK AS GIVEN IN OFFICE RECORDS
NOTES:
1. VARIES FROM YEAR TO YEAR. VALUE GIVEN HERE BASED ON 19-YEAR SERIES OF TIDE OBSERVATIONS ENDING IN 1978, BY THE NATIONAL OCEAN SURVEY (FORMERLY USC & GS).
2. A FIXED REFERENCE ADOPTED AS A STANDARD GEODETIC DATUM FOR ELEVATIONS IN THE UNITED STATES OF AMERICA. FORMERLY REFERRED TO AS MEAN SEA LEVEL (MSL) DATUM, BUT NOT TO BE CONFUSED WITH LOCAL MEAN SEA LEVEL.
3. BASED ON ANNUAL SERIES DATA ADJUSTED TO PRESENT SEALEVEL CONDITIONS
● HIGH WATERMARK - OCTOBER 1991
STATUTE MILES
NEW ENGLAND COASTLINE
TIDAL FLOOD SURVEY
TIDAL FLOOD PROFILE NO. 11
COHASSET, MASS. TO GEORGETOWN, MAINE
DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION, CORPS OF ENGINEERS
WALTHAM, MASS.
SEPTEMBER 1988

APPENDIX B

GLOSSARY

Accretion - May be either natural or artificial. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a beach by deposition of waterborne or airborne material. Artificial accretion is a similar buildup of land by reason of an act of man, such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means.

Anticyclone - An extensive system of winds circling clockwise (in the northern hemisphere) outward from a high pressure center.

Backshore - The zone of the shore or beach lying between the foreshore and the coastline and acted upon by waves only during severe storms, especially when combined with exceptionally high water.

Beach - The zone of sedimentary material that extends landward from the low water line to the place where there is marked change in material or form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach - unless otherwise specified - is the mean low water line. A beach includes foreshore and backshore.

Beach Berm - A flat terrace located at the top of the foreshore. Also, a nearly horizontal part of the beach or backshore formed by the deposit of material by wave action. Some beaches have no berms, others have one or several.

Beach Erosion - The carrying away of beach materials by wave action, tidal currents, littoral currents or wind.

Beach Width - The horizontal dimension of the beach measured perpendicular to the shoreline.

Blowout - The rapid erosion, loss of material, and subsequent breakthrough of a dune system resulting from storm waves and high water levels.

Bluff - A high, steep bank composed of erodible materials.

Coast - The strip of land, of indefinite width (up to several miles), that extends from the shoreline inland to the first major change in terrain features.

Continental Shelf - The zone bordering a continent and extending from the low-water line to the depth (usually about 100 fathoms) where there is a marked or rather steep descent toward a greater depth.

Convergence - In refraction phenomena, the decreasing of the distance between orthogonals in the direction of wave travel. Denotes an area of increasing wave height and energy concentration.

Coriolis Effect - The apparent deflection of moving objects from a straight path caused by earth rotation. Moving bodies appear deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

Cyclone - Air masses circulating counterclockwise (in the northern hemisphere) about a low pressure center.

Deep Water - Water so deep that surface waves are little affected by the ocean bottom. Generally, water deeper than one-half the surface wavelength is considered deep water.

Divergence - In refraction phenomena, the increasing of distance between orthogonals in the direction of wave travel. Denotes an area of decreasing wave height and energy concentration.

Dune - Ridge or mound of loose, windblown material, usually sand.

Erosion - The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation.

Extratropical - An east coast storm (except a hurricane) of the middle Atlantic and New England states that produces strong onshore winds. Also known as a northeaster.

Eye - In meteorology, usually the "eye of the storm" (hurricane); the roughly circular area of comparatively light winds and fair weather found at the center of a severe tropical cyclone.

Fetch - The continuous area of open water over which the wind blows in a constant direction. In enclosed bodies of water, it would usually coincide with the longest axis in the general wind direction.

Fetch Length - The horizontal distance (in the direction of the wind) over which a wind blows to generate seas or to create a wind setup.

Foreshore - The part of the shore lying between the crest of the seaward berm (or upper limit of wave wash) and the water's edge at low water. The foreshore is ordinarily traversed by the runup and return of the waves.

Gale - A wind having a speed between 32 and 63 miles per hour.

Generation of Waves - (1) The creation of waves by natural or mechanical means. (2) The creation and growth of waves caused by a wind blowing over a water surface for a certain period of time.

Hurricane - An intense tropical cyclone in which winds tend to spiral inward toward a core of low pressure, with maximum surface wind velocities that equal or exceed 75 miles per hour (65 knots) for several minutes or longer at some points. Tropical storm is the term applied if maximum winds are less than 75 miles per hour.

Lee - Shelter, or the part or side sheltered or turned away from the wind or waves.

Lithified - Refers to rocky or hardened sediments.

Littoral Drift - The sedimentary material moved along the shoreline under the influence of waves and currents.

Littoral Transport - The movement of littoral drift along the shoreline by waves and currents. Includes movement parallel (longshore transport) and perpendicular (on-offshore transport) to the shore.

Littoral Zone - In beach terminology, an indefinite zone extending seaward from the shoreline to just beyond the breaker zone.

Longshore - Parallel to and near the shoreline.

Mean High Water (MHW) - The average height of the high waters over a 19-year period. For shorter periods of observations, corrections are applied to eliminate known variations and reduce the results to the equivalent of a mean 19-year value.

Mean Low Water (MLW) - The average height of the low waters over a 19-year period. For shorter periods of observations, corrections are applied to eliminate known variations and reduce the results to the equivalent of a mean 19-year value.

Mean Sea Level - The average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings.

Morphology - In geology, the visual shape of landscape features, either singly or as a group in a given area.

Nautical Mile - The length of a minute of arc, 1/21,600 of an average great circle of the earth. Generally 1 minute of latitude is considered equal to 1 nautical mile. The accepted United States value as of 1 July 1959 is 6,076.115 feet or 1,852 meters, approximately 1.15 times as long as the statute mile of 5,280 feet.

Neap Tide - A tide having about 10 to 30 percent less range than the average, occurring about the time of quarter moons.

Nearshore (zone) - In beach terminology an indefinite zone extending seaward from the shoreline well beyond the breaker zone.

Offshore - The direction away from the shore, toward a large body of water. Also, the comparatively flat zone of variable width, extending from the breaker zone to the seaward edge of the Continental Shelf.

Onshore - The landward direction, away from the water.

Orthogonal - A line perpendicular to a wave crest.

Overtopping - The passing of water over the top of a natural or man-made structure as a result of wave runup or surge.

Perigean Tides - Tides of increased range occurring monthly as the result of the moon being in perigee, or closest to the earth.

Propagation of Waves - The transmission of waves through water.

Refraction (of Water Waves) - (1) The process by which the direction of a wave moving in shallow water at an angle to the contours is changed. The part of the wave advancing in shallower water moves more slowly than that part still advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours. (2) The bending of wave crests by currents.

Revetment - A facing of stone, concrete, etc., built to protect a scarp, embankment or shore structures against erosion by wave action or currents.

Riprap - A layer, facing or protective mound of stones randomly placed to prevent erosion, scour or sloughing of a structure or embankment; also the stone so used.

Rubble-mound Structure - A mound of randomly shaped and randomly placed stones protected with a cover layer of selected stones or specially shaped concrete armor units.

Runup - The rush of water up a beach or structure, associated with the breaking of a wave. The amount of runup is measured according to the vertical height above still water level that the rush of water reaches.

Scour - Removal of underwater material by waves and currents, especially at the base or toe of a shoreline structure.

Seas - Waves caused by wind at the place and time of observation.

Seawall - A structure separating land and water areas, primarily designed to prevent erosion and other damage due to wave action.

Sediment - Solid material, both mineral and organic, that is in suspension, is being transported or has been moved from its site of origin by air, water or ice and has come to rest on the earth's surface either above or below sea level.

Shallow Water - Commonly, water of such a depth that surface waves are noticeably affected by bottom topography. It is customary to consider water of depths less than one-half the surface wavelength as shallow water.

Shoal - A detached elevation of the sea bottom, comprised of any material except rock or coral, which may endanger surface navigation.

Shore - The narrow strip of land in immediate contact with the water, including the zone between high and low water lines. See also backshore and foreshore.

Shoreline - The intersection of a specified plane of water with the shore or beach (e.g., the high water shoreline would be the intersection of the plane of mean high water with the shore or beach.) The line delineating the shoreline on U.S. Coast and Geodetic Survey nautical charts and surveys approximates the mean high water line.

Significant Wave - A statistical term relating to the one-third highest waves of a given wave group and defined by the average of their heights and periods. The composition of the higher waves depends upon the extent to which the lower waves are considered. Experience indicates that a careful observer who attempts to establish the character of the higher waves will record values which approximately fit the definition of the significant wave.

Spring Tide - A tide that rises highest and falls lowest from mean sea level, occurring at new or full moon.

Storm - Winds ranging from 64 to 72 miles per hour.

Storm Surge - A rise above normal water level on the open coast due to the action of wind stress on the water surface. Storm surge resulting from a hurricane also includes that rise in level due to atmospheric pressure reduction as well as that due to wind stress.

Swell - Wind-generated waves that have traveled out of their generating area. Swell characteristically exhibits a more regular and longer period and has flatter crests than waves within their fetch (SEAS).

Syzygy - The time of a new or full moon in the moon's cycle of phases.

Tidal Range - The difference in height between consecutive high and low (or higher high and lower low) waters.

Tide - The periodic rising and falling of water that results from gravitational attraction of the moon and sun acting on the rotating earth.

Updrift - The direction opposite that of the predominant movement of littoral materials.

Wave Height - The vertical distance between a wave crest and the preceding trough.

Wave Hindcasting - The use of historic synoptic wind charts to calculate characteristics of waves that probably occurred at some past time.

Wave Length - The horizontal distance between similar points on two successive waves (for example, crest to crest or trough to trough), measured in the direction of wave travel (perpendicular to the crest).

Wave Period - The time in which a wave crest travels a distance equal to one wave length. Can be measured as the time for two successive wave crests to pass a fixed point.

Windward - The direction from which the wind is blowing.

APPENDIX C

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REFERENCES

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APPENDIX D

WAVE & WATER LEVEL HINDCAST

Wind Wave and Water Level Hindcast Results for the Blizzard of 1978 and Halloween Storm of 1991 for Coastal New England

Prepared for
U.S. Army Engineer Division, New England

by

J. M. Hubertz and W. R. Curtis

Final Report - June 1993

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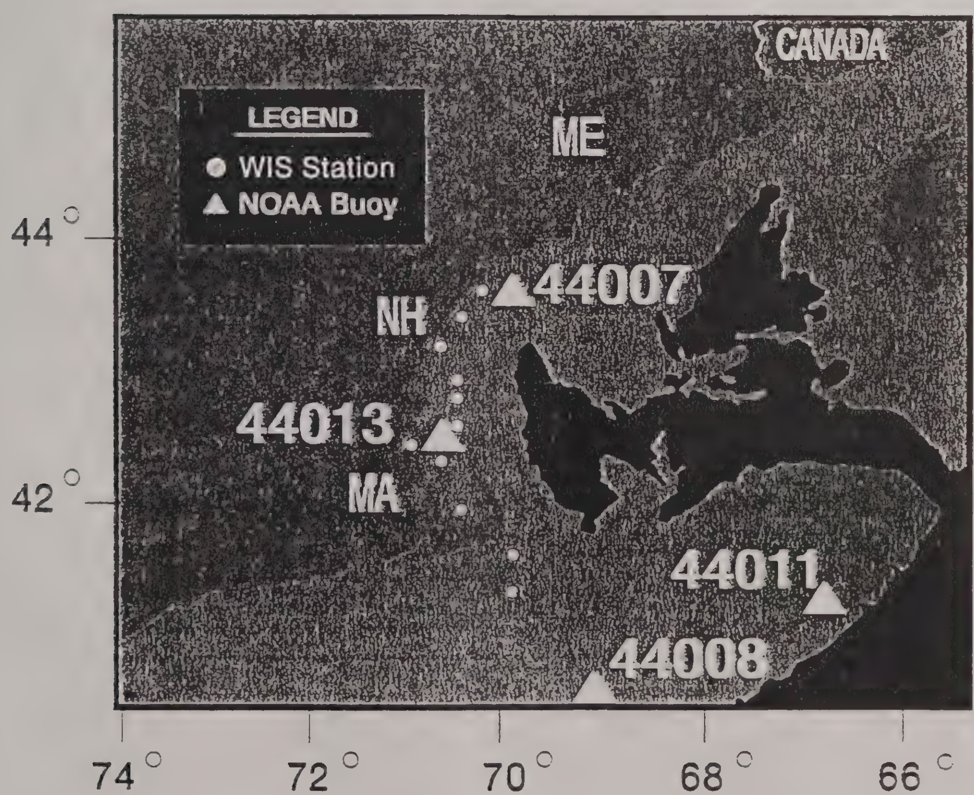

ABSTRACT

The Wave Information Study at the Coastal Engineering Research Center conducted a wave and water level hindcast for the New England Division (NED) for the Blizzard of February 1978 and Halloween Storm of 1991. Wave and water level information is supplied at 13 stations along the New England coast. The objective of the study was to calculate this information so personnel at NED could conduct studies correlating coastal damage to wave and water level conditions along the coast for these two storms.

Hindcast wave and water level information for the Halloween storm was compared to available measurements. No measured wave data were available from the Blizzard of 1978, but water levels were compared at three sites. Hindcast wind speeds and directions generally agree with measurements to within 1-2 m/sec and 10-20 degrees, respectively. Hindcast wave heights and peak and mean periods agree with measured values to within 1 m, 4-5 sec, and 1-2 sec, respectively. Water levels at the peak of the storms agree with measurements to within 0.5 m.

A regional analysis of hindcast wave and water level information indicates the Blizzard of 1978 was probably more damaging to the northern region of coastline (approximately between Portland, ME and Portsmouth, NH) than the Halloween storm due to higher wave heights and water levels. The Halloween storm was probably more damaging to the Cape Cod and Nantucket regions than the Blizzard of 1978 due to higher wave heights and longer wave periods, and the longer duration of extreme conditions.

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PREFACE

The U.S. Army Corps of Engineers Division, New England (CENED) requested the Wave Information Study (WIS) at the Coastal Engineering Research Center (CERC), Waterways Experiment Station (WES) to hindcast water levels and wave heights for the Halloween Storm of October 1991 and the Blizzard of February 1978. Hindcast results will be used by NED to study damage effects of the two northeasters on the coastline of New England between Nantucket, MA and Portland, ME.

The water level and wave hindcast study was conducted by Dr. Jon Hubertz and Mr. William R. Curtis of the Coastal Oceanography Branch (COB), Research Division (RD), CERC. The wind fields used in this study were prepared by Mrs. Rebecca Brooks, COB. Ms. Robin J. Hoban, COB, prepared the cover drawing and assembled the report.

The study was conducted under the direct supervision of Dr. Martin C. Miller, Chief, COB and Mr. H. Lee Butler, Chief, RD. General supervision was provided by Mr. Charles C. Calhoun, Jr. Assistant Chief, CERC, and Dr. James R. Houston, Chief, CERC. Mr. John Kedzierski was Technical Project Manager (TPM) for CENED.

Dr. Robert W. Whalin was director of WES. COL. Leonard G. Hassell, EN was Commander and Deputy Director.

WIND WAVE AND WATER LEVEL HINDCAST
FOR THE BLIZZARD OF 1978 AND HALLOWEEN STORM OF 1991

INTRODUCTION

On 6 February 1978, an extratropical storm (northeaster) occurred off the New England coastline. Commonly referred to as the Blizzard of 1978, this storm produced wind gusts in excess of 41.0 m/sec and sustained winds of 27.0 m/sec. Strong easterly winds combined with high astronomical tides resulted in storm surges on the order of 1 m above National Geodetic Vertical Datum (NGVD) and storm waves ranging from 3.0 to 9.0 m along the coastline from Nantucket, MA to Portland, ME (Fair and Feit, 1978).

Between 28 October and 1 November 1991, a northeaster occurred off the New England coastline producing flooding and damage similar to the Blizzard of 1978. This storm is commonly referred to as the Halloween Storm. The Halloween Storm produced severe environmental conditions, with measured wave heights approaching 13 meters and measured wave periods in excess of 15 seconds in the New England coastal region. This storm was classified as an extreme northeaster, Class 5 (Dolan and Davis, 1992). Maximum storm surges were on the order of 1 m, for example, 1.1 m at Portland ME, 1.6 m at Boston MA, 1.4 m at Nantucket, MA, and 1.3 m at Woods Hole, MA.

This water level and wave hindcast study was conduucted as part of a Coastal Storm Evaluation Study being accomplished by New England Division (NED). Measured wave data along the coast of New England is virtually nonexistent for the Blizzard of 1978 and the Halloween Storm of 1991. Therefore wave climate information must be provided by employing established numerical hindcast techniques. However measured water level data are available at the following gage sites within the study area and were supplied by NED; Nantucket, MA, Portland, ME, and Boston, MA.

The objectives of this study are to conduct wave and water level hindcasts of the Blizzard of 1978 and Halloween Storm for the New England region, and supply information at five nautical mile increments along the coast from Nantucket, MA to Portland, ME (refer to Scope of Work in Appendix A). Wave hindcasts are accomplished by applying historical meteorological data to the Wave Information Studies (WIS) wave model WISWAVE 2.0 (Hubertz, 1992). Historical meteorological and tide data are used with the storm surge model SURGE II (Reid, et al., 1977) to hindcast water levels along the coast due to the extratropical events. Hindcast results are then compared to limited wave climate and water level observations to verify model calculations for the two storms. Results generated by the models will be used by NED to reveal trends and correlate areas of property damage due to storm induced flooding and erosion with predicted water level and wave height information.

WIND AND WAVE HINDCAST

Wave hindcast calculations were made using the WIS wave model WISWAVE 2.0 (Hubertz, 1992). WISWAVE 2.0 is a second generation discrete directional spectral model. It is presently the Corps' operational spectral wave model and has been in use since 1987. Operation of the model is described in WIS Report 27, (Hubertz, 1992). The model is available within the Coastal Modeling System for use by Field personnel. It is a second generation wave model. First generation wave models do not include wave-wave interactions and only implement empirical growth and dissipation algorithms. Second generation wave models account for the transfer of energy within the spectrum by functions dependent on a number of parameters. These are referred to as parameterized nonlinear wave-wave interaction terms. Growth and dissipation terms can be included in addition to these terms. Third generation wave models attempt to explicitly calculate the wave-wave interactions rather than representing them as a function of various parameters. These models are presently moving from a research mode to consideration for operational use, based on their ability to calculate wave conditions more accurately than models presently in use.

The first version of WISWAVE was used to produce 32 years of hindcast wave data for the Great Lakes, (Hubertz, et al. 1991). That version did not include the effects of shallow depths (refraction and shoaling) on wave propagation. The second version includes these effects and is the version used in this study. It was also the version used to produce the 20 years of revised wave information for the U.S. East coast, (Hubertz et al., 1993). Work is underway now to include the effects of currents on wave propagation. When those changes are implemented, the model will be upgraded to version 3.0.

The present version allows a discrete representation of the directional bands. It has a wind source term which allows growth of wave energy and a parameterized nonlinear wave-wave interaction term which controls the shape of the spectrum as it develops. The model is forced by windfields over the gridded region of interest. The model can employ sub-grids to provide wave information at higher resolution in space if required. This is referred to as a nested grid capability.

Wave information can be output at specific locations or over regions. Simple wave parameters such as height, period, and direction can be output or more detailed information such as frequency spectra or frequency / direction spectra, if desired. Several post processing programs exist to summarize the wave information or calculate major components of the spectra.

No calibration of the model is considered necessary since the model has been applied extensively by CERC and typically achieves an accuracy of +/- 0.5 m and +/- 2-3 sec for wave height and peak period respectively, (Hubertz et al., 1993). The accuracy of wave information from a model is very much a function of the accuracy of winds in space and time over the water body where waves are generated and propagated. Attempts to improve wave results (calibration) are usually not done by adjusting model coefficients, but by trying to improve the representation of the wind

fields. WISWAVE 2.0 has produced acceptable wave information for studies in the Great Lakes, Gulf of Mexico, Pacific Ocean, and Atlantic Ocean without changing any model coefficients.

Hindcasts for the Blizzard of 1978 and Halloween Storm incorporated 16 direction bands encompassing 360 degrees, and 20 frequency bands corresponding to wave periods of: 28.0, 24.0, 22.0, 20.0, 19.0, 18.0, 17.0, 16.0, 15.0, 14.0, 13.0, 12.0, 11.0, 10.0, 9.0, 8.0, 7.0, 6.0, 5.0, 4.0 sec. Numerical grids applied in WISWAVE 2.0 were composed of latitude and longitude lines. Numerical grid information including land-sea matrices and bathymetry (depths measured at MLW) were obtained from nautical charts. A nested grid application was employed, where offshore boundary information was saved to serve as input to a higher resolution numerical grid encompassing a smaller geographical area.

Figure 1 shows the hindcast region for grid level 1. The grid used in level 1 is a 0.5 degree (30 nautical mile) grid encompassing a significant area of the northwest Atlantic including the entire eastern coastline of the United States (Figure 2). Both storm systems occurred in the open ocean beyond the continental shelf region of the eastern United States. Therefore, a large grid is necessary to model waves generated in the open ocean subsequently propagating into the New England coastal region. Water deep enough not to affect wave propagation (999 m) was assumed in level 1 with the exception of the continental shelf region where a constant value of 90 m was used. Figure 3 shows the region covered in level 2 of the hindcast. The grid in level 2 is a 5 nautical mile grid covering the New England region from just south of Cape Cod, MA to just north of Portland, ME. Wave energy generated in grid level 1 is input to grid level 2 as a boundary condition at the open circled points in Figure 3. The land boundary is shown by solid dots. Wave propagation with wind effects takes place between the circled points (boundary condition from level 1) and the land boundary. Model results compared best to buoy data at locations 44007 and 44013 when assuming deep water between the boundary condition points and the land boundary. Model results at the 13 points of interest are shown by squares and numbered as in Appendix F.

Wave and water level information was saved at 13 locations which are of most interest to NED at this time. Information at all grid points is potentially available. These 13 locations are numbered 1-13 and referred to as such in Table 1 under "Model" and in Figures 28-46 and Appendices B-E. The location of stations closest to shore is provided in Appendix F, numbered 1-73, and referred to by number in Table 1 under "Appendix". The land boundary schematized in Figure 3 may not accurately show the location of land with respect to the grid lines due to the resolution of the coastline. Plotting the station locations on a nautical chart using latitudes and longitudes will give a more accurate representation.

Wind fields for the Blizzard of 1978 were obtained from Oceanweather Inc. and covered the period 0000 05 February 1978 through 0000 09 February 1978 in 6 hour increments. Times are referenced to the Universal Time Coordinate (UTC). Original wind fields obtained from Oceanweather Inc. were at 0.5 degree grid resolution and were applied to grid level 1 at 20

meters elevation. Higher resolution wind fields for grid level 2 were obtained by bilinearly interpolating velocity components applied to grid level 1.

Wind fields for the Halloween Storm were obtained from Oceanweather Inc. at 0.5 degree grid resolution and 10 meters elevation. Halloween Storm wind fields included the period 0000 28 October 1991 through 0012 1 November 1991 in 1 hour increments. Times are referenced to the Universal Time Coordinate (UTC). One-half degree grid resolution wind fields were applied to grid level 1. Higher resolution wind fields applied to grid level 2 were obtained by bilinearly interpolating velocity components of grid level 1 wind fields. Wind speeds may be adjusted to be applicable at different elevations between 0 and 20 m using equation 3-26 on page 3-26 of the SPM.

Table 1

Locations of Hindcast Wave and Water Level Information

Station Number Model	/Appendix	Location	Grid Level 2 (I,J)	Lat. Deg. Min.	Long. Deg. Min.
1	72	Buoy 44007	12,32	43 30	70 05
2	13	Saco Bay	9,32	43 30	70 20
3	18	Wells, ME	7,29	43 15	70 30
4	25	Hampton Beach, NH	4,25	42 55	70 45
5	30	Rockport, MA	6,22	42 40	70 35
6	31	Eastern Point, MA	6,21	42 35	70 35
7	73	MA Disposal Site	6,19	42 25	70 30
8	37	Hull, MA	3,18	42 20	70 50
9	38	Buoy 44013	4,18	42 20	70 45
10	40	Scituate, MA	5,17	42 15	70 40
11	48	Sandwich, MA	8,12	41 50	70 25
12	66	Chatham, MA	14,10	41 40	69 55
13	71	Sankaty Head Light, MA	14,5	41 15	69 55

No measured wave data are available for the duration of the Blizzard of 1978. NDBC buoy stations in the New England region and neighboring offshore regions were not operational as early as February 1978. Thus, we cannot present any comparison to measured data for this storm. It is assumed that the wave hindcast results for the Blizzard of 1978 are of comparable quality to those from the Halloween Storm since the same methods and wave model were used, and winds were derived from the same source.

For the duration of the Halloween Storm, measured wave data for the New England region were collected and analyzed by NDBC to provide full spectral wave data for NDBC buoy locations 44007, 44008, 44011 and 44013 (Figure 1). Basic wind and wave parameters include wind speed and wind direction, average and dominant (peak) wave period and significant wave height. No wave direction data are available from NDBC buoys in the New England region.

Spectral wave heights are calculated by WISWAVE 2.0. Spectral wave heights are based on integration of energy over the discrete spectrum. These model wave heights are equivalent to those obtained from NDBC buoy measurement and analyses.

Peak or dominant periods are not integral quantities. That is, they are not derived by summation over the spectrum. Peak period is defined as the period associated with the mid-band frequency of the frequency band containing the largest spectral energy density. It is possible for spectra to have a multi-modal distribution of energy versus frequency. For example, spectra may have two peaks representing sea and swell. Differences in peak period for a case like this may range over several seconds. This may introduce large differences in peak period comparisons between measured and hindcast results. For example, it is possible that the peak period is associated with local seas in hindcast calculations, while peak period is associated with swell in the buoy measurements for the same time period. Therefore, if two periods were calculated from the gage spectrum and two from the hindcast spectrum, corresponding measured and predicted results would likely be in agreement.

Average wave period is available from NDBC buoy data analysis. A similar parameter, mean wave period, is calculated by WISWAVE 2.0. Mean wave period is an energy-weighted quantity integrated over all specified frequencies of interest. Since mean period is an integral quantity over all frequencies, it may not be representative of periods associated with sea or swell. Unless integrated over a large single peaked spectrum, mean period will not represent the period associated with peak spectral energy density. It is peak period rather than mean period that is generally associated with coastal engineering design considerations.

The factors affecting comparisons of wave parameters are discussed in more detail in WIS Report 30, (Hubertz, et al., 1993). To avoid some of the problems of comparing peak periods, spectra can be compared to determine how energy is distributed in different frequency bands. These more detailed comparisons are beyond the scope of this study.

Although wave direction information is not available from NDBC buoy locations in the New England region, WISWAVE 2.0 predictions of mean wave direction are presented characterizing direction in the spectrum. Mean direction is defined as the energy-weighted mean direction over all frequency bands.

NDBC buoys 44008 and 44011 are located on the seaward edge of the Georges Bank in depth of about 65 m (Figure 1). The closest level 1 grid points are (26,32) and (32,34) counting from left to right and bottom to top from the lower left hand corner, respectively (Figure 2). NDBC buoy location 44008 (40.5 N, 69.4 W) is located approximately 60 nm southeast of Nantucket at about 55 m depth. NDBC buoy location 44011 (41.1 N, 66.6 N) is located approximately 150 nm east of Cape Cod, MA at approximately 88 m depth. Wave climate data at stations 44008 and 44011 are representative of the continental shelf region off New England for the duration of the Halloween Storm.

Figures 4–8 show hindcast versus measured results at buoy 44008 for wind speed, wind direction, wave height, and wave peak and mean period, respectively. Fixed values for the Y-axis range are used in all subsequent plots to make comparisons easier. Wind speeds generally agree within 3–5 m/sec and directions within 10–20 degrees. Wave heights agree well during the development of the storm, but over predict by about 1.5 m during the peak and decay of the storm. Peak periods agree within 3 sec and reach maximum values of 15 and 16.5 sec, respectively, for hindcast and buoy. Model mean periods are consistently higher than buoy by 1–2 sec. This could be due to the different number of frequency bands and distribution of energy in the measured and modeled spectra. The model has 20 bands while the buoy has about twice as many with most being at higher frequencies. Since the mean period is an energy-weighted quantity, more weight will be given to the higher frequencies in the buoy spectrum, provided there is energy in that portion of the spectrum. The model spectrum, having no equivalent frequencies, would result in lower mean periods. Figure 9 shows mean wave direction from the model. Waves are generally coming from between 10 and 60 deg, or from north to northeast. There are no measured directional data for comparison.

Figures 10–14 show results for the same quantities at buoy 44011. Wind speeds again agree within 3–5 m/sec and directions within 10–20 degrees. Hindcast wave heights agree with measured values. Generally, hindcast wave heights are within 0.5 m of measured wave heights, and both reach maximum values of 12 m. Hindcast peak periods tend to be low at the peak of the storm by 4–6 sec. Hindcast mean periods are high by 2–3 sec. These differences are attributed to mis-representation of the wind field during the peak of the storm which could result from improper wind speeds, directions, fetches, and or durations within the storm area. Figure 15 shows mean wave direction from the model. Waves are coming from the north during the beginning of the storm, from the northeast at the peak, and from the east during decay of the storm. There are no measured directional data for comparison.

NDBC buoy station 44007 (43.5 N, 70.1 W) is located approximately 12 nm east of Saco River Bay at 30.0 m depth. Figures 16–20 show model versus measured results at buoy 44007 for wind speed, wind direction, wave height, and wave peak and mean period, respectively. Hindcast wind speeds agree with measured values within 1–2 m/sec. Wind directions agree within 10–20 degrees. Hindcast and measured wave heights agree during development of the storm, but are high with respect to measurements by 1 m during storm decay. This may be due to excess swell energy at the site. Wind speeds at the buoy agree well, so it is unlikely the higher waves are due to local sea. Both hindcast and measured values reach maximum values of 6–7 m. Hindcast and measured peak periods generally agree within 4–5 sec. The differences in peak period between hours 15 and 50 are likely due to the presence of sea and swell and determination of peak period as discussed above on page 6. Hindcast values are low at the peak of the storm. Hindcast and measured mean periods agree within 1–2 sec and both reach peak values of 10–11 sec. Figure 21 shows hindcast mean wave direction. Waves are generally from the east for the duration of the storm. There are no measured directional data for comparison.

NDBC buoy location 44013 is located outside Boston Harbor (42.4N, 70.8W) at approximately 30.0 m depth. Figures 22-26 show model versus measured results at buoy 44013 for wind speed, wind direction, wave height, and wave peak and mean period, respectively. Hindcast wind speeds agree with measured values within 2 m/sec, and directions within 10-20 degrees. Hindcast wave heights agree with measured values within 1 m, and both reach maximum values of 8-9 m. Hindcast and measured values of peak period agree within 2-4 sec with hindcast values being low at the peak of the storm. Hindcast and measured mean periods agree within 1-2 sec, and both reach maximum values of 11 sec. Figure 27 shows hindcast mean wave direction. Waves are generally from the east for the duration of the storm. There are no measured directional data for comparison.

Wave height and period comparisons are summarized at buoy locations 44007 and 44013 since this study is concerned primarily with these variables near shore. Hindcast wave height results are considered an accurate representation of actual conditions to within 1 m. Hindcast peak and mean periods are considered an accurate representation of actual conditions to within 2-4 and 1-2 sec, respectively. Hindcast peak periods are low at the peak of the storm by about 4 sec, reaching values of 14-15 sec versus measured values of 17-20 sec. Hindcast and measured mean period values agree at the peak of the storm, reaching values of 11 sec. Considering the complexity of this storm and scope of this study, this level of agreement is the best attainable and should be acceptable to contrast the severity of the two storms at different coastal locations.

WATER LEVEL CALCULATIONS

Total water level (astronomical tide and wind setup) was calculated with the Surge II model using the same level 2 grid and winds as used for the wave hindcast. Water level is referenced to the National Geodetic Vertical Datum (NGVD) of 1929. Ocean boundary conditions were developed from tide gage records at Portland, ME and Boston, MA and Nantucket, MA.

SURGE II is a program for calculation of storm surge and tides in a bay, estuary, or open coast. It includes the provision for sub-grid scale barriers and channels as well as allowing for overtopping of barriers and flooding of and recession from normally dry regions. These features were not included in the scope of the present study. The model employs the vertically integrated equations of motion and continuity neglecting advective and Coriolis terms. It is driven by wind stress over a square grid and by water level boundary conditions. A time dependent explicit finite difference formulation, centered in space and time, is used to solve the equations. The model gives most accurate results when lateral gradients in the flow are small and bottom friction dominates Coriolis effects. These conditions should apply for this case. Calibration to measurements will improve results. Input boundary conditions were adjusted in this application to obtain general agreement with tide gage measurements in the vicinity of model grid points.

Figures 28-30 show comparisons of hindcast water levels to measured at the station closest to gage locations at Portland, ME, Boston, MA, and

Nantucket, MA for the Blizzard of 1978. Note that hindcast output station and gage location can differ significantly in location due to the resolution of the hindcast grid. The scope of the present study did not allow for use of CERC's latest model which could provide results at points close to the actual measurement sites with possibly better agreement. The peak of this storm occurs about hour 60 on the plots. Hindcast and measured water levels differ by less than 0.5 m at this time. During the peak of the storm water levels are at the + 2.5-3.0 m NGVD level at each location. This represents a surge (water level in excess of normal astronomical tide) of about 1 m along the coast.

Figures 31-33 show comparisons of hindcast water levels to measured values for the same locations as Figures 28-30 for the Halloween Storm of 1991. The peak of this storm occurs between hours 50 and 60 on the plots. Peak water levels are between the + 2.5-3.5 m NGVD levels. Hindcast and measured water levels differ by less than 0.5 m at the peak of the storm. Surge levels, for this storm, at these locations are approximately the same as for the Blizzard of 1978.

COMPARISON OF WAVE CONDITIONS AND WATER LEVELS FOR THE BLIZZARD OF 1978 AND THE HALLOWEEN STORM OF 1991

One objective of this study is to provide information on wave and water level conditions during the Blizzard of 1978 and Halloween storm of 1991 in order to make qualitative and quantitative comparisons of these conditions to relate to damage along the coast. This is done by providing information at 13 locations specified by NED in both graphical and tabular format. Appendices B and C contain detailed tabulated wave information at these locations for the 1978 and 1991 storms, respectively. Appendices D and E contain tabulated water level information at these locations at the same times for the 1978 and 1991 storms, respectively.

Figures 34-46 provide a graphical comparison of wave height, peak period and water level between the Blizzard of 1978 and Halloween Storm of 1991 at the 13 stations designated by NED. These parameters are designated Hs, Tp, and H, respectively, in the figures. These parameters are considered important in relation to beach damage during storms and are the primary input parameters to the coastal processes model SBEACH (Rosati, et al., 1993). An example of how these figures might be used is provided in Table 2.

Table 2

Wave and Water Level Conditions at Peak of Storms by Station

	Station #	Hs (m)	Tp (sec)	H(m)*	Duration (hrs)
1978	1	8.5	13	3.0	25
1991	1	6.5	15	1.0	23
1978	2	7.5	13	3.0	20
1991	2	6.0	14	1.3	15
1978	3	7.5	12	3.0	20
1991	3	6.0	16	1.8	18
1978	4	8.0	12	3.2	25
1991	4	7.0	13	1.8	25
1978	5	8.0	12	3.2	30
1991	5	8.0	13	2.0	35
1978	6	8.0	12	3.0	33
1991	6	8.2	13	2.4	33
1978	7	8.2	12	3.4	35
1991	7	8.4	13	2.4	35
1978	8	8.5	12	3.5	25
1991	8	7.5	14	2.2	27
1978	9	8.5	12	3.5	27
1991	9	8.0	13	2.5	30
1978	10	8.2	12	3.4	30
1991	10	8.3	13	2.3	33
1978	11	5.6	10	2.0	5
1991	11	8.9	13	3.4	28
1978	12	8.0	12	2.5	44
1991	12	10.0	14	2.5	75
1978	13	8.0	12	3.0	45
1991	13	11.5	15	3.0	70

* Datum is NGVD

This table was constructed by examining each figure and determining the peak value of Hs, the peak period at the approximate time of occurrence of the peak wave height, the water level at the time of high tide closest to the time of peak wave height, and the duration in hours when wave heights were above 5 m at each station for each storm. The value of 5 m was chosen

arbitrarily. These values characterize conditions during the peak of the storms.

Stations 1-4 are located between Portland, ME and Portsmouth, NH. At stations 1-4, wave heights and water levels are higher by 1-2 m for the 1978 storm than for the 1991 storm. Duration for conditions when wave heights exceeded 5 m is approximately the same for both storms, and peak periods are lower for the 1978 storm than for the 1991 storm. Thus, at these stations one might expect more beach damage from the 1978 storm than for the 1991 storm due to larger wave heights and water levels.

Conditions at stations 5-10 (from Cape Ann south to Scituate, MA) are approximately equivalent for both storms, with the exception of water level being consistently higher during the 1978 storm. Thus, potential for damage was probably somewhat higher for the 1978 than 1991 storm along this section of the coast due to higher water levels.

There appears to be a much higher potential for damage from the 1991 versus 1978 storm at stations 11-13 . Station 11 is in the interior of Cape Cod Bay and Stations 12 and 13 are near Chatham and Nantucket, MA, respectively. Wave heights are larger, and periods and duration are longer for the 1991 than for the 1978 storm. Water levels are also higher in Cape Cod Bay during the 1991 storm. Water levels are the same at stations 12 and 13 on the open coast.

The analysis above is an example of how the hindcast results can be used to assess damage potential on a regional basis.

SUMMARY

Two severe extratropical events, the Blizzard of 1978 (February 1978) and the Halloween Storm (October 1991) occurred off the New England coastline. Both storms produced extensive damage due to incident wave energy and coastal flooding. The New England Division wishes to correlate regional wave and water levels to damage estimates. However, limited wave and water level measurements exist for the New England region for the duration of both storms. Therefore, a wave and water level hindcast was conducted for the New England region for the Blizzard of 1978 and Halloween Storm to supply estimates of environmental conditions. Hindcast estimates were compared to measurements when available. No measurements are available for the Blizzard of 1978.

The Halloween Storm was a part of a complex meteorological system occurring off the eastern United States, as an extratropical storm and Hurricane Grace occurred simultaneously and later merged. Development of accurate wind fields for the storm is extremely intricate considering the complexity of the system combined with spacial and temporal scales. Wind field results presented in this report represent the best estimates available to date.

Hindcast wave height results are considered an accurate representation of actual conditions to within 1 m. Hindcast peak and mean periods are

considered an accurate representation of actual conditions to within 2–4 and 1–2 sec, respectively. Hindcast peak periods are low at the peak of the storm by about 4 sec, reaching values of 14–15 sec versus measured values of 17–20 sec. Hindcast and measured mean period values agree well at the peak of the storm, both reaching values of 11 sec. Hindcast water levels are considered accurate to within 0.5 m at the peak of the storms. These results are considered the best attainable within the cost limits of the study.

A regional analysis of hindcast results was made which indicates the Blizzard of 1978 may have had more potential to damage the northern part of the New England coast while the Halloween storm likely had more potential to damage the southern part of the region.

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LIST OF FIGURES

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Figure 37. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 4.

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Figure 39. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 6.

Figure 40. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 7.

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Figure 42. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 9.

Figure 43. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 10.

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Figure 45. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 12.

Figure 46. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 13.

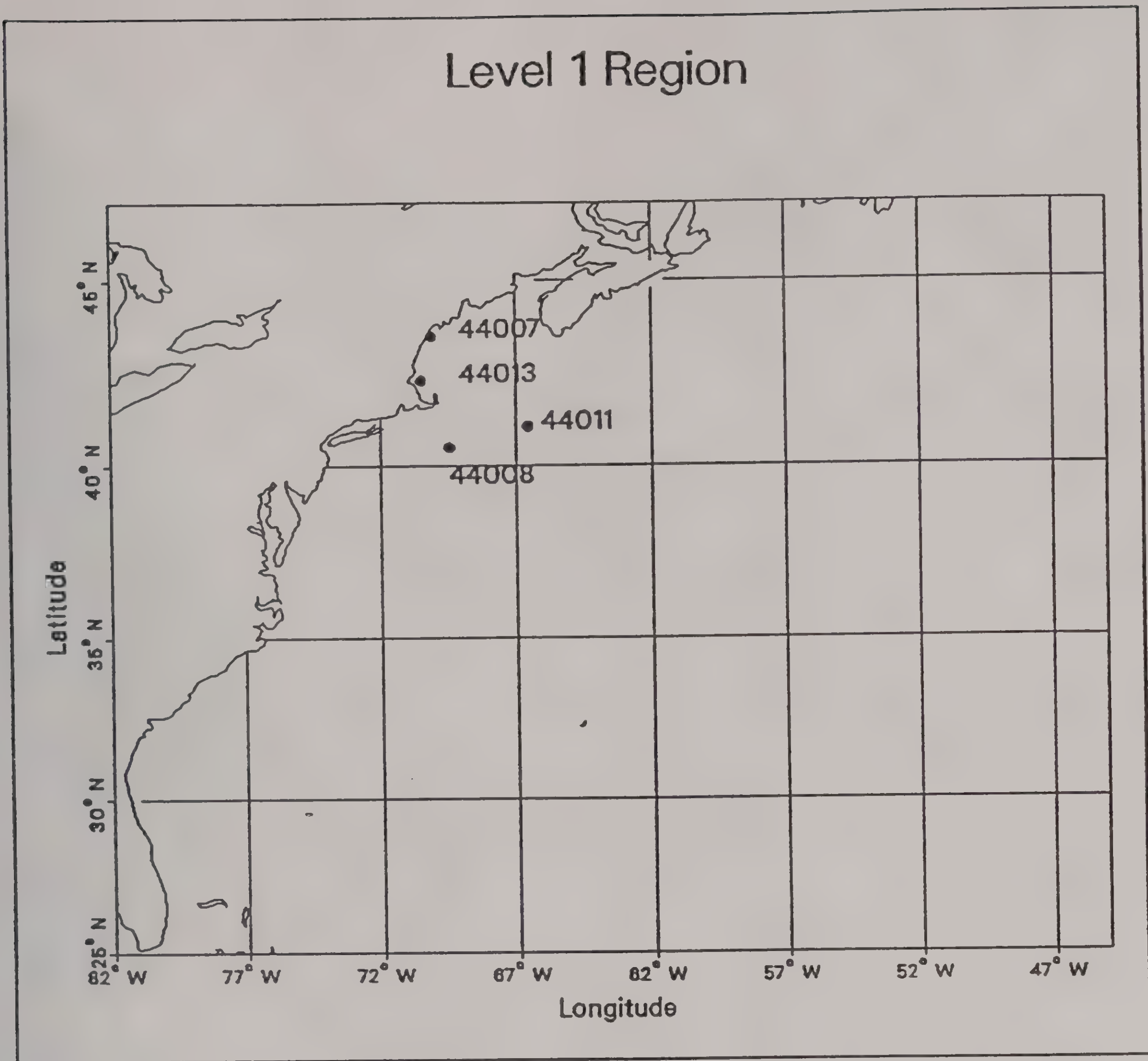


Figure 1. Level 1 hindcast region. Solid dots and numbers indicate locations of NOAA buoys.

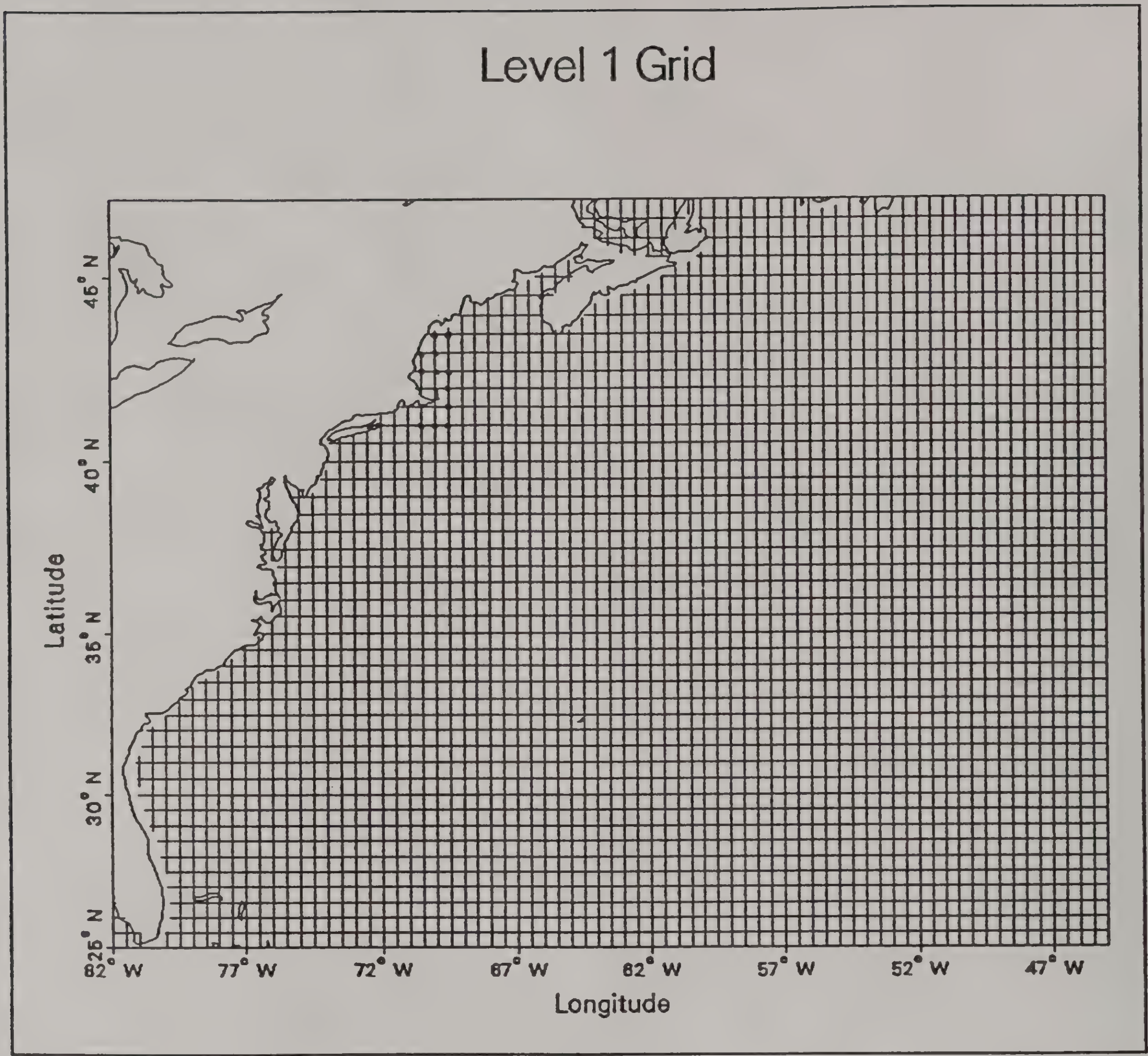


Figure 2. Numerical grid for hindcast level 1 region. Grid rows and columns increase sequentially up and to the right respectively from (1,1) in the lower left corner to (75,47) in the upper right.

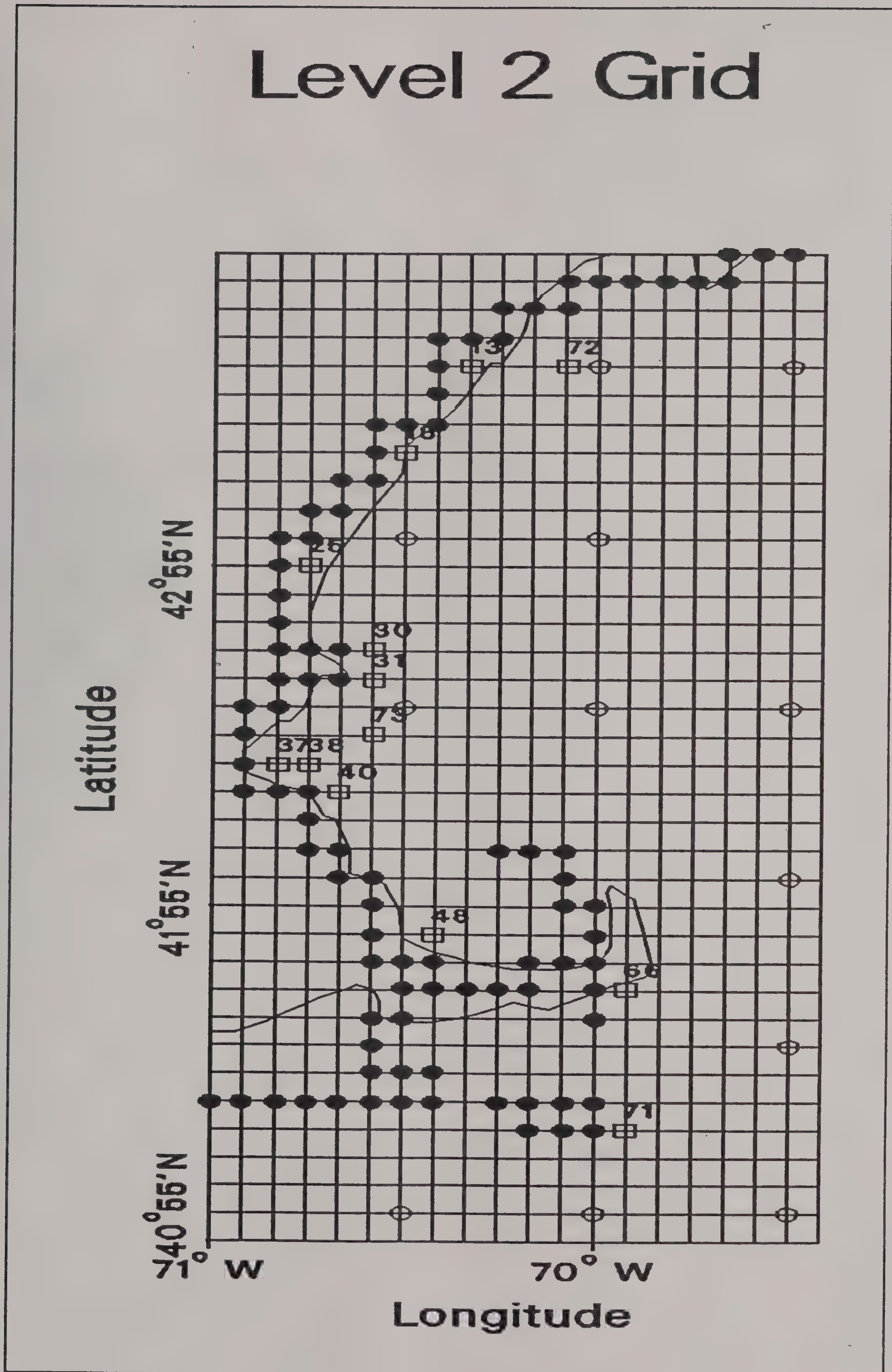


Figure 3. Numerical grid for hindcast level 2 region. Grid rows and columns increase sequentially up and to the right respectively from (1,1) in the lower left corner to (36,20) in the upper right.

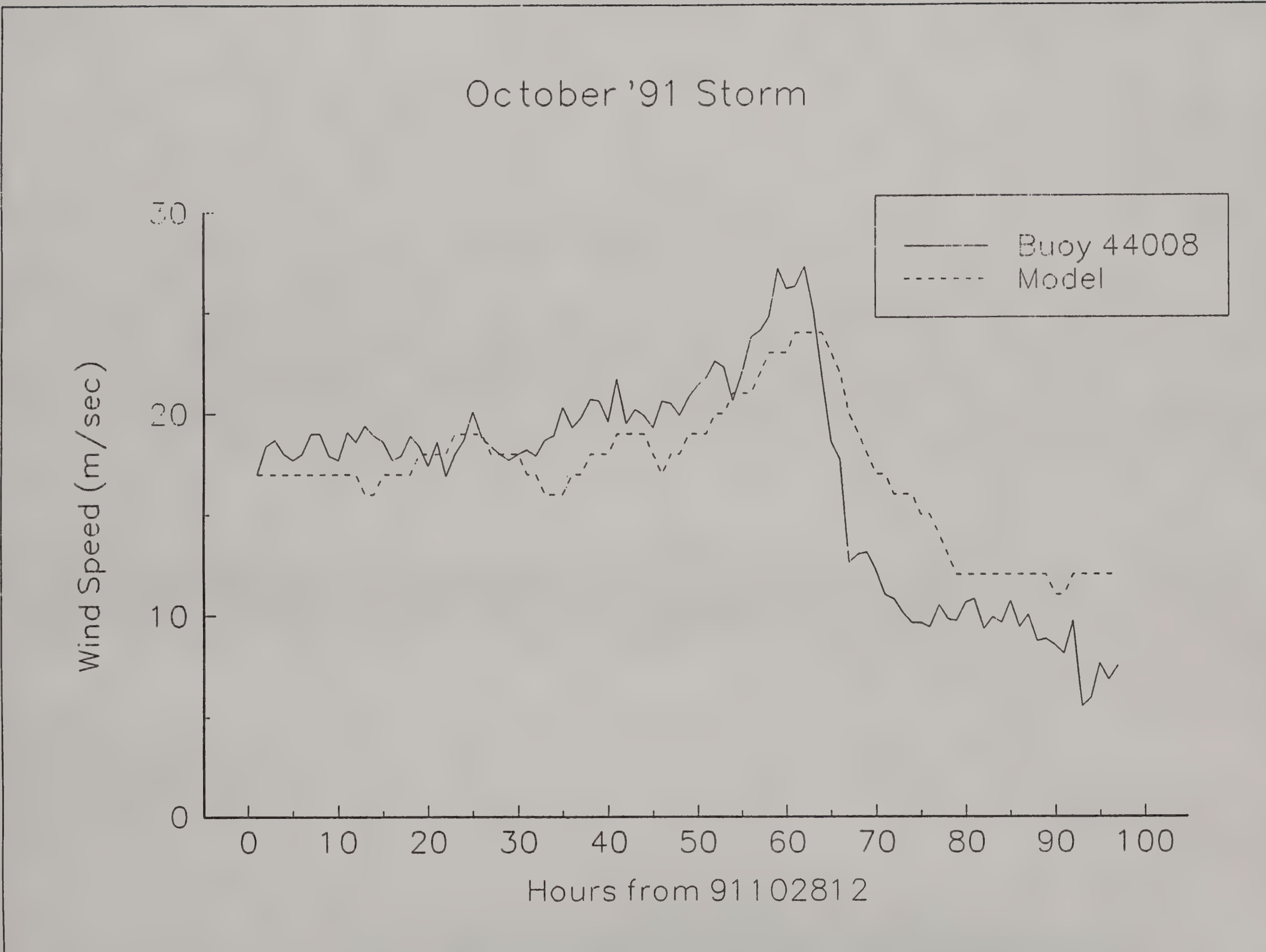


Figure 4. Measured and hindcast wind speed during the Halloween storm of 1991 at NOAA buoy 44008 location.

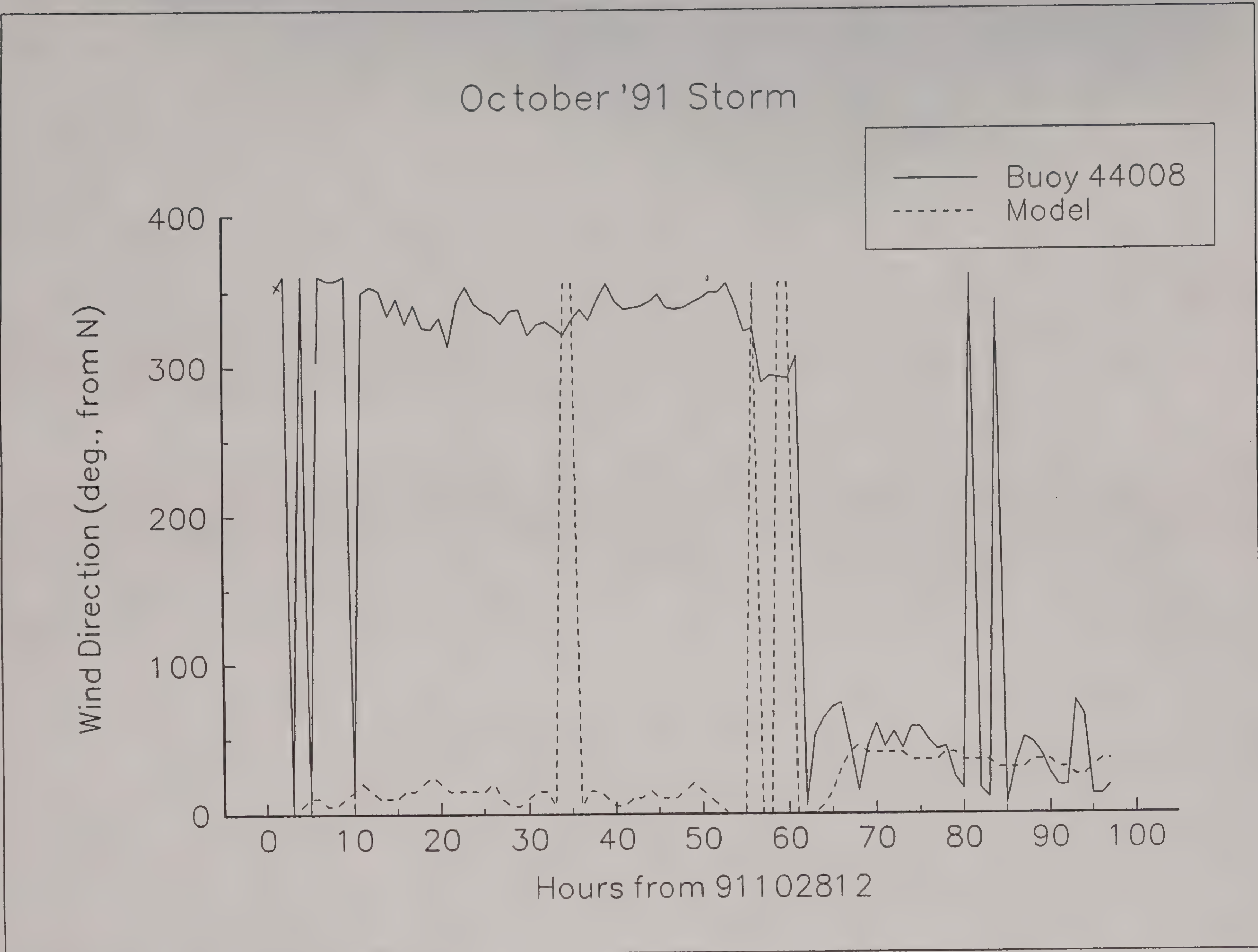


Figure 5. Measured and hindcast wind direction during the Halloween storm of 1991 at NOAA buoy 44008 location.

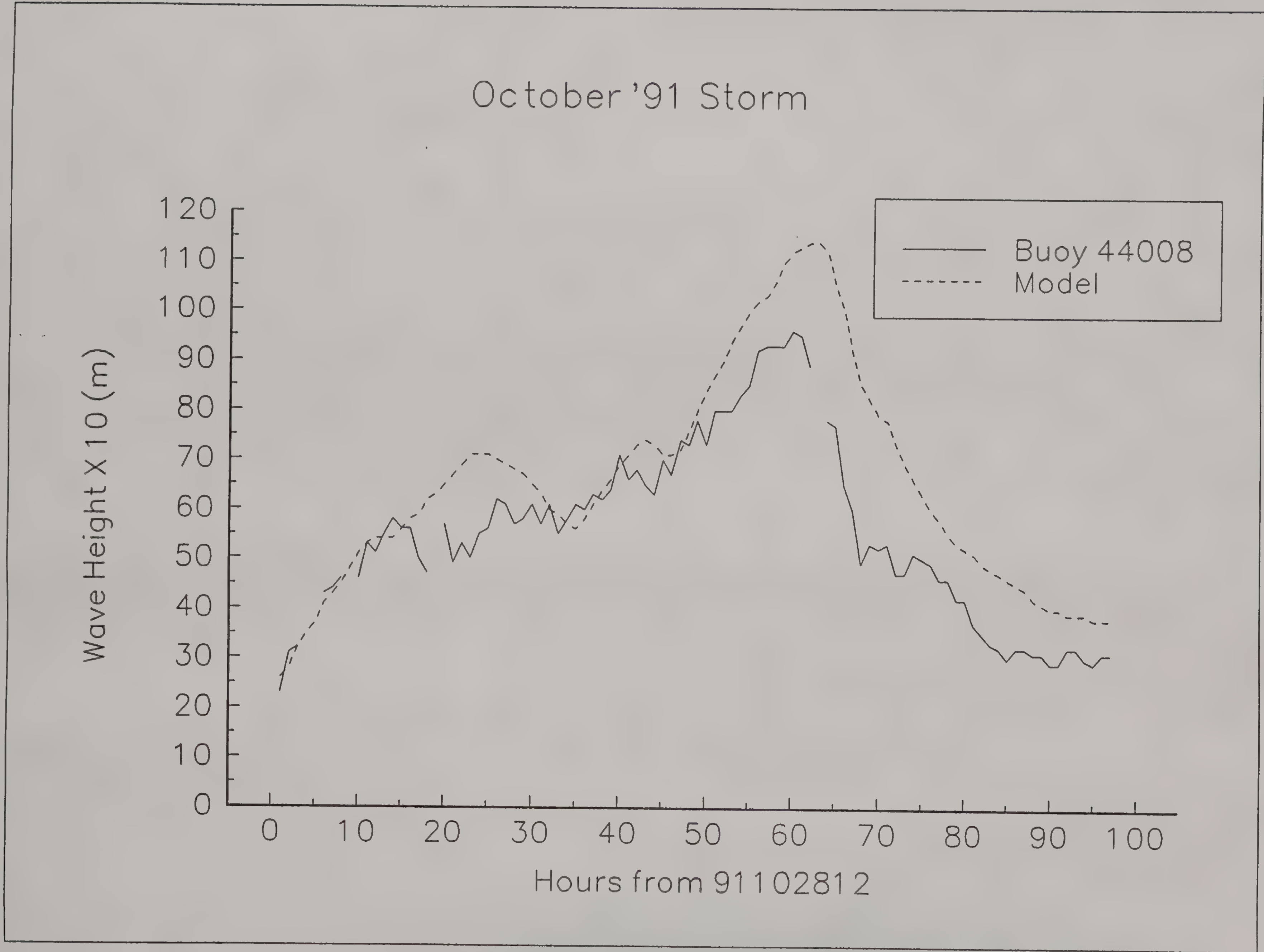


Figure 6. Measured and hindcast wave height during the Halloween storm of 1991 at NOAA buoy 44008 location.

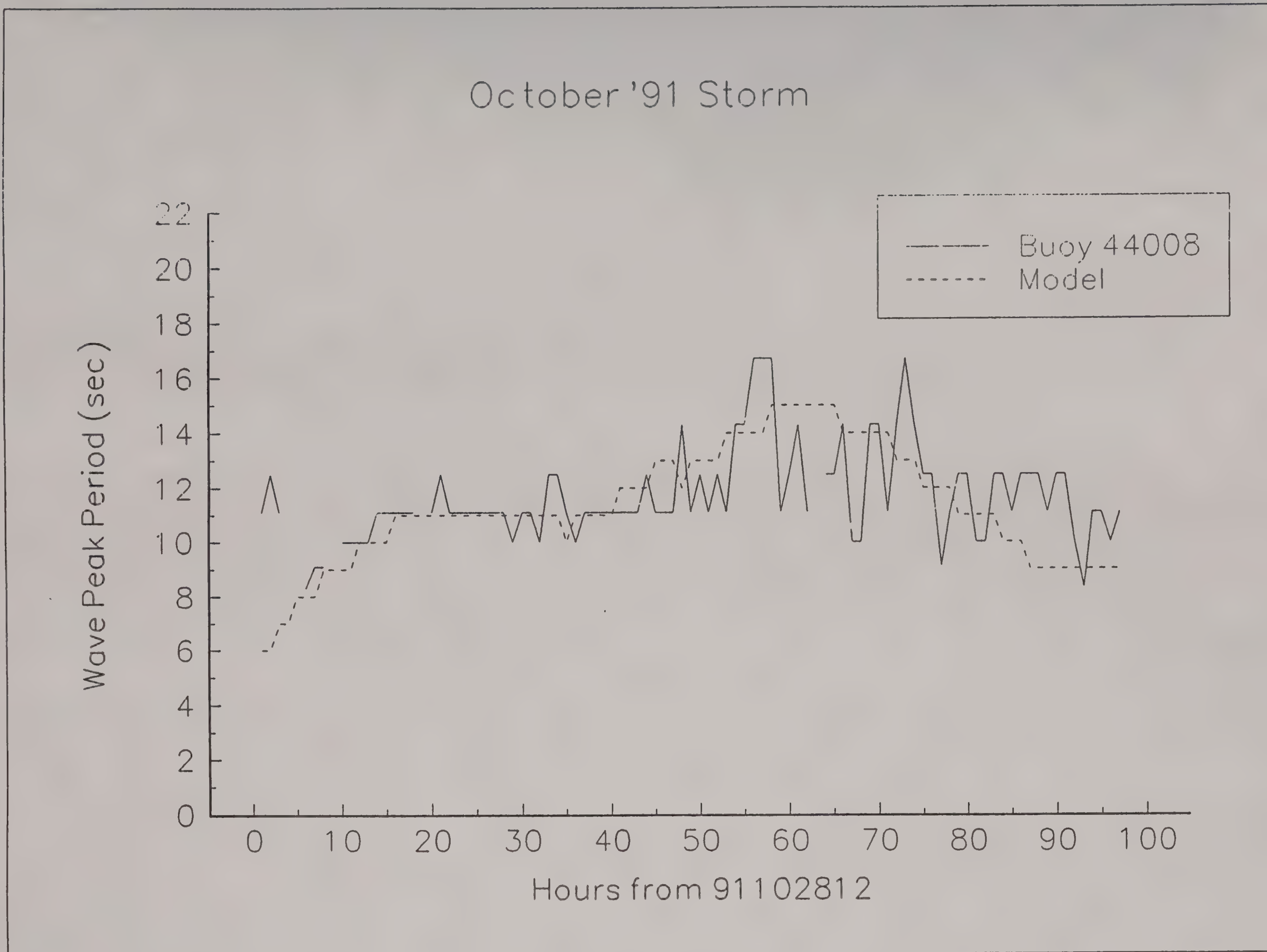


Figure 7. Measured and hindcast wave peak period during the Halloween storm of 1991 at NOAA buoy 44008 location.

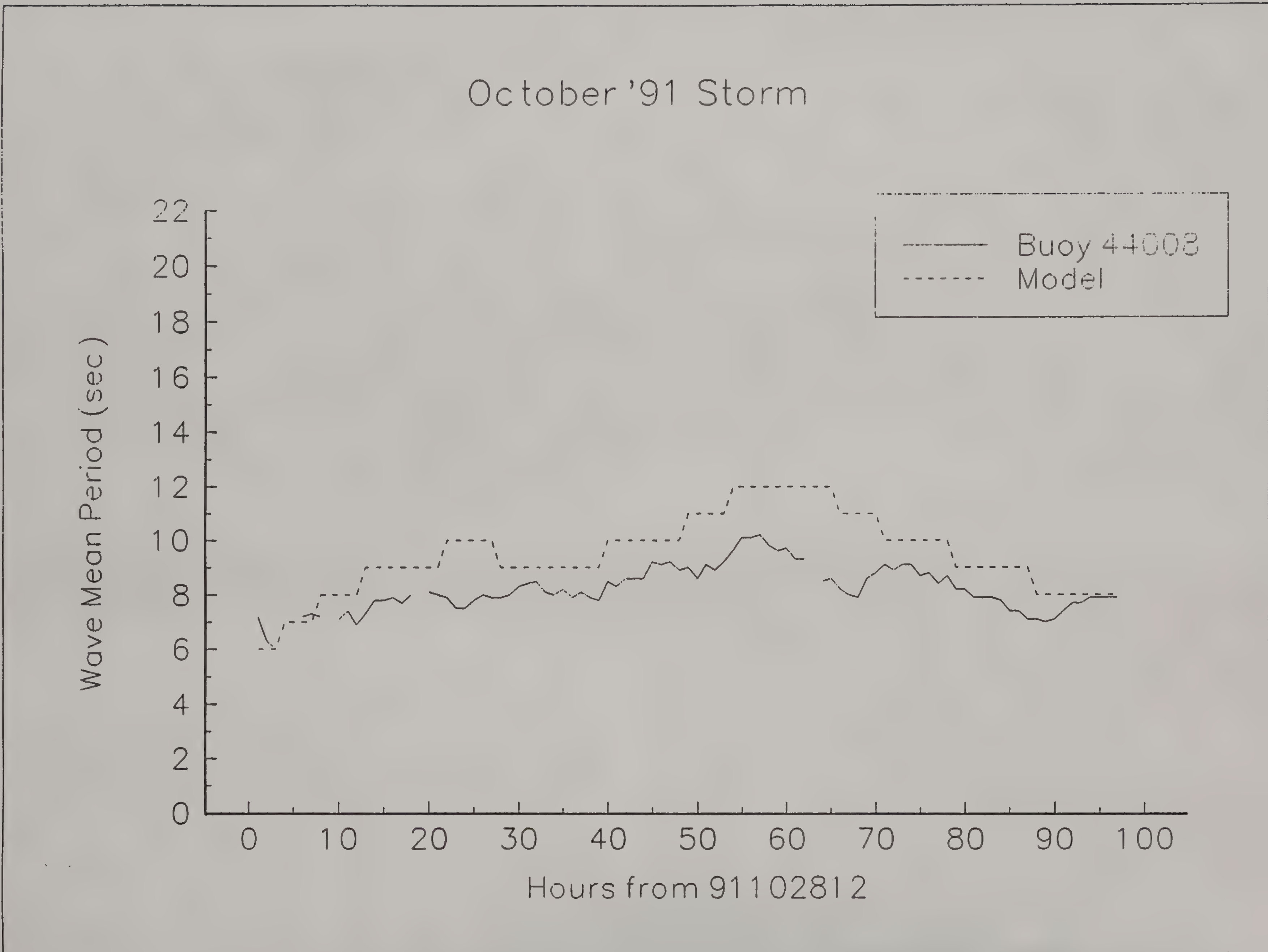


Figure 8. Measured and hindcast wave mean period during the Halloween storm of 1991 at NOAA buoy 44008 location.

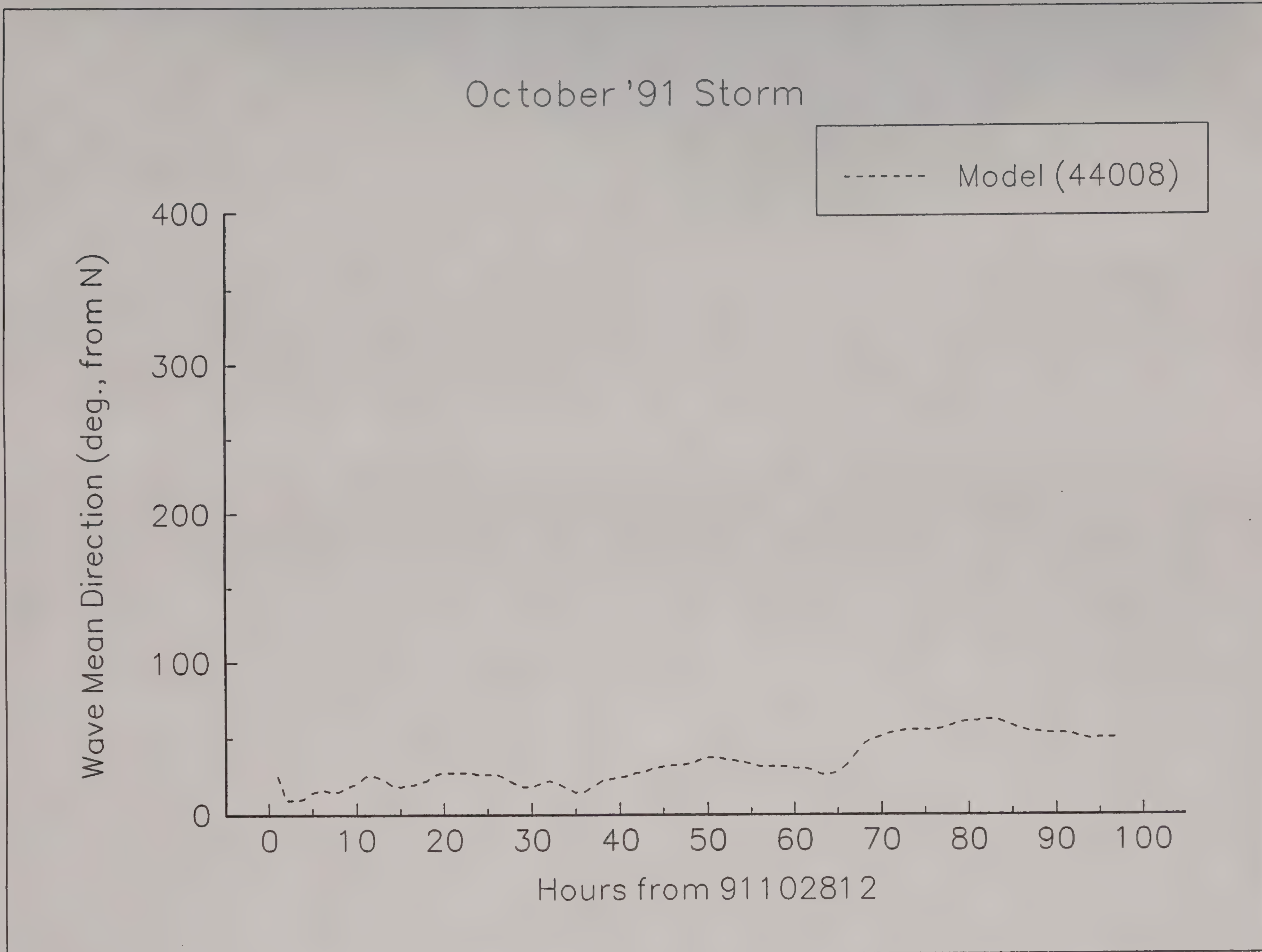


Figure 9. Hindcast mean wave direction during the Halloween storm of 1991 at NOAA buoy 44008 location.

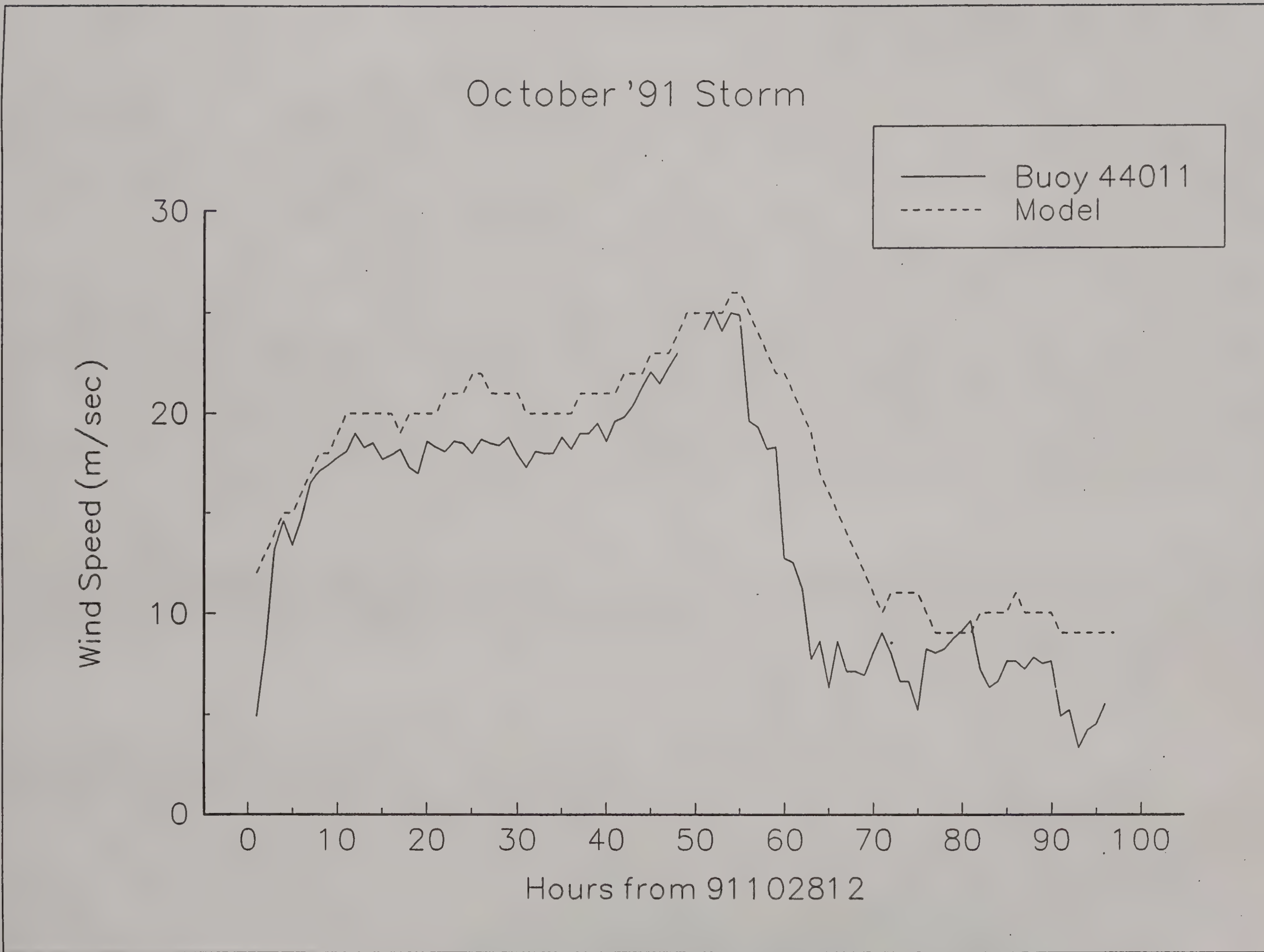


Figure 10. Measured and hindcast wind speed during the Halloween storm of 1991 at NOAA buoy 44011 location.

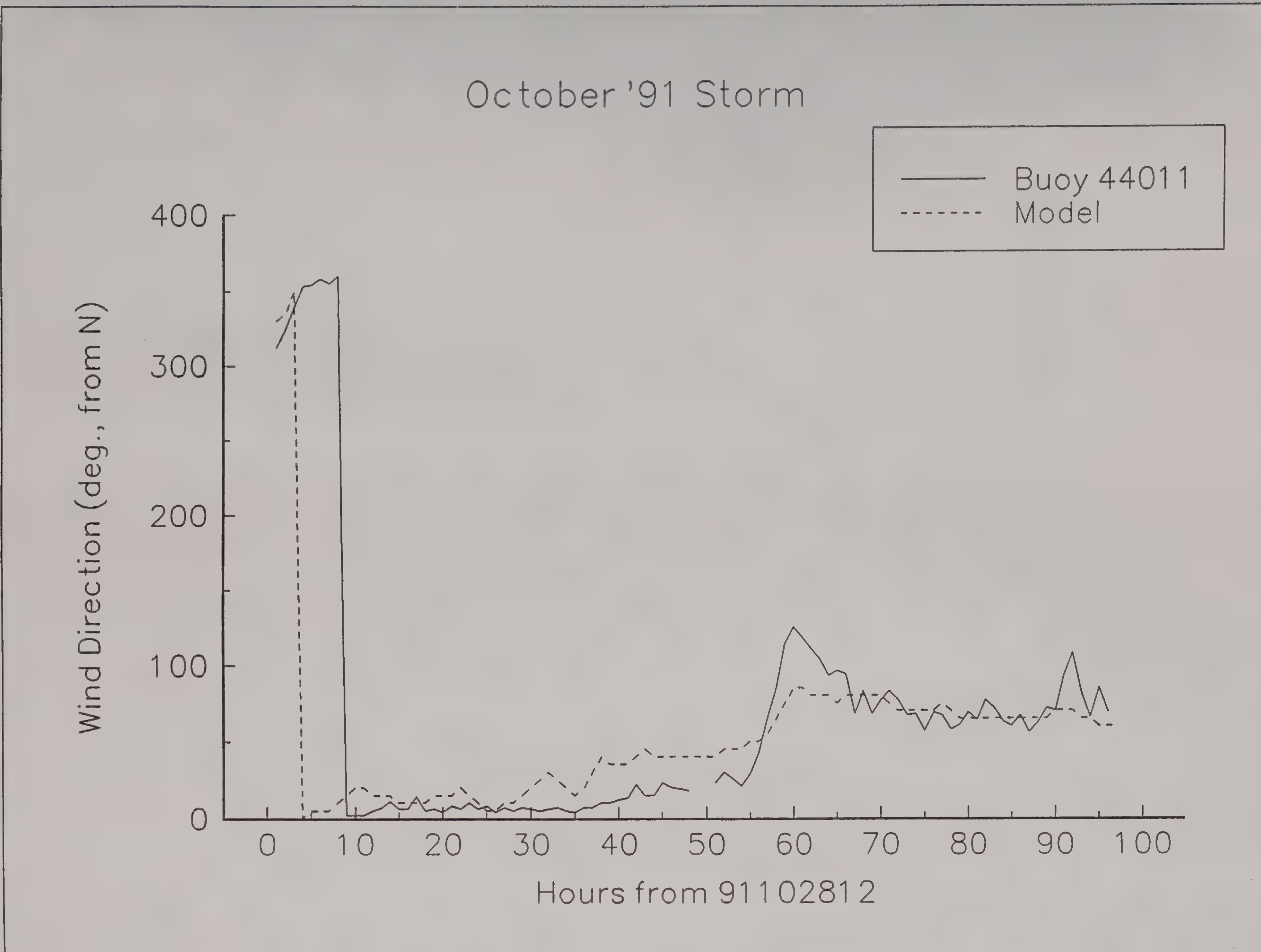


Figure 11. Measured and hindcast wind direction during the Halloween storm of 1991 at NOAA buoy 44011 location.

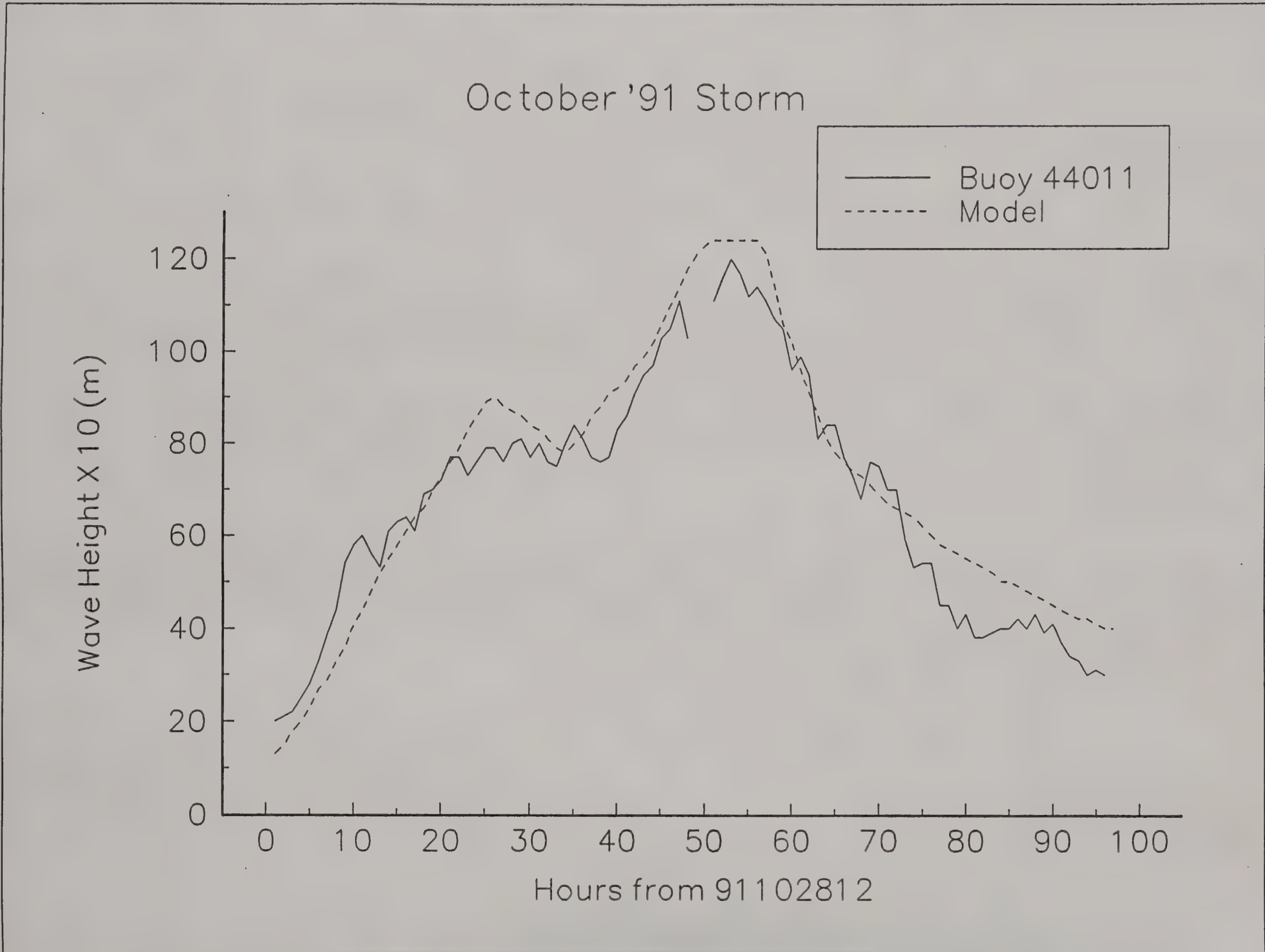


Figure 12. Measured and hindcast wave height during the Halloween storm of 1991 at NOAA buoy 44011 location.

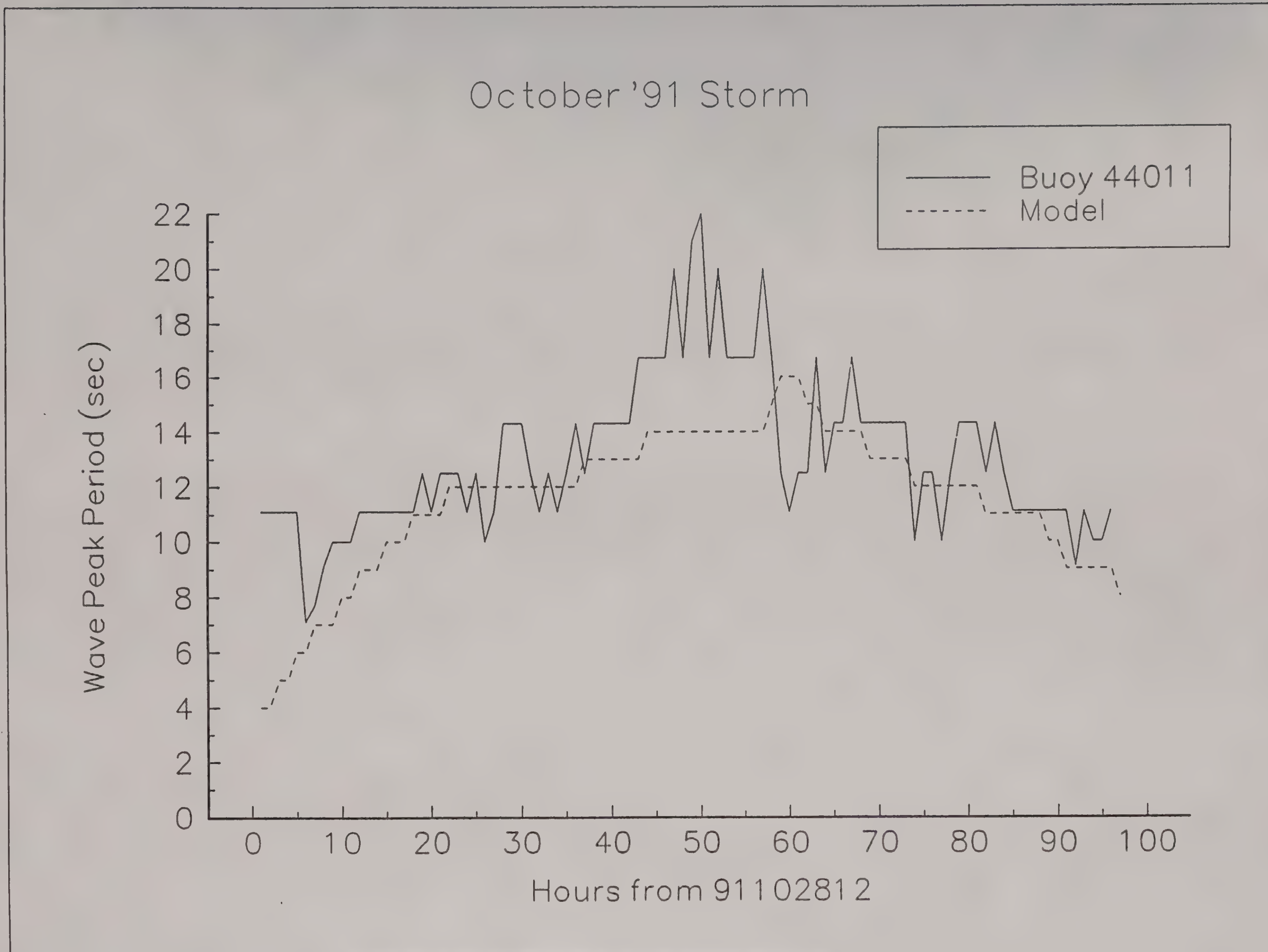


Figure 13. Measured and hindcast wave peak period during the Halloween storm of 1991 at NOAA buoy 44011 location.

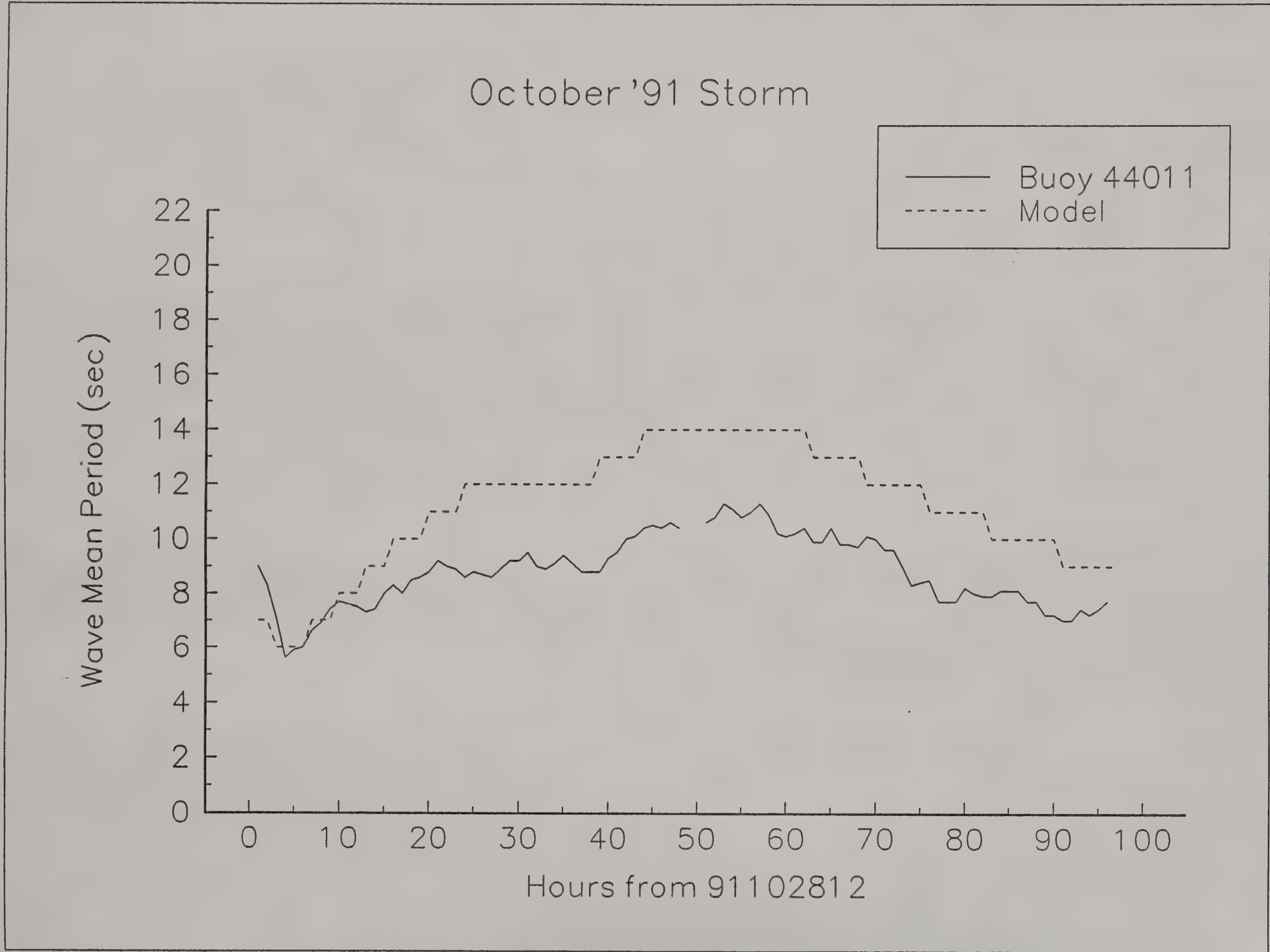


Figure 14. Measured and hindcast wave mean period during the Halloween storm of 1991 at NOAA buoy 44011 location.

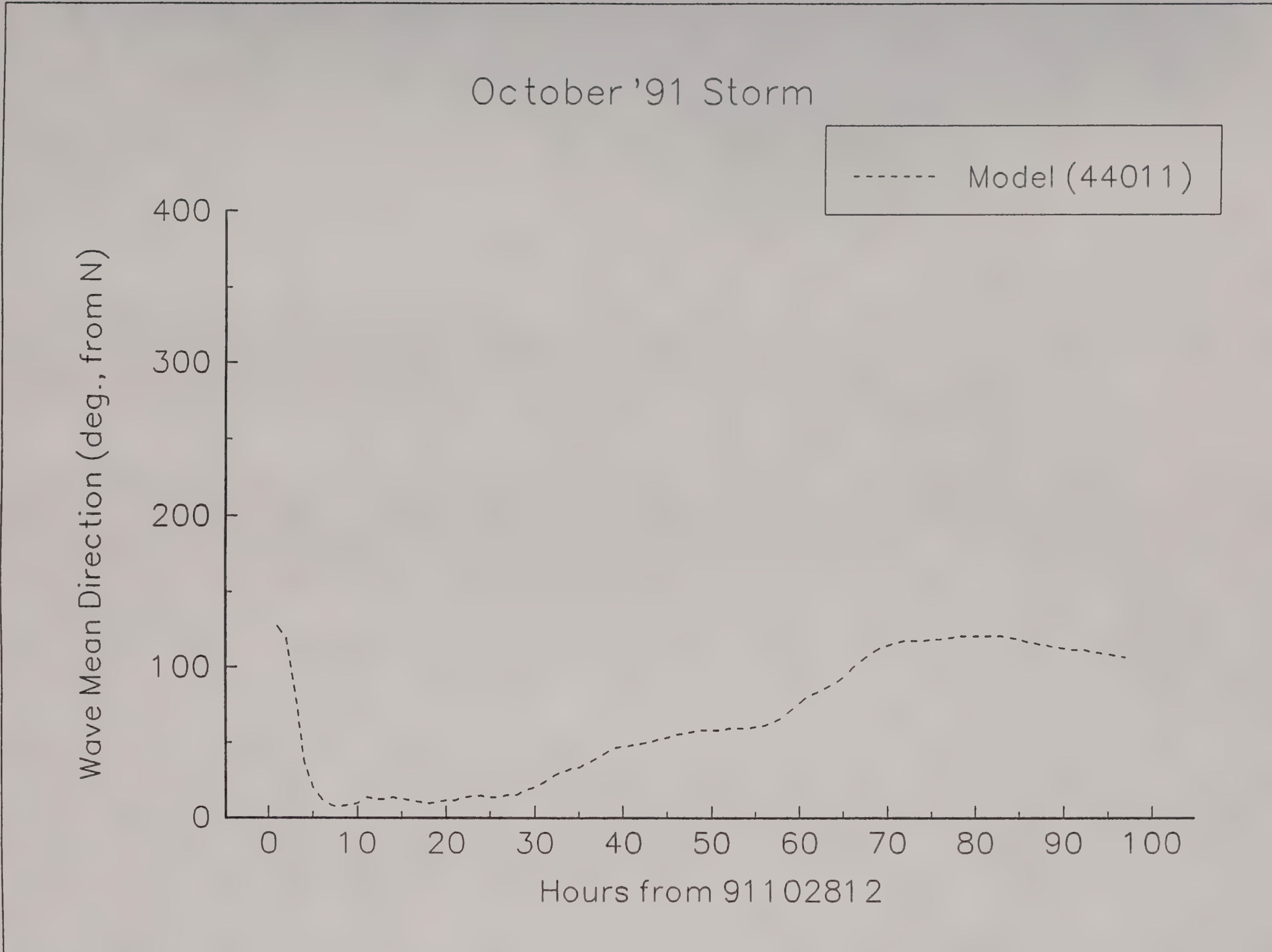


Figure 15. Hindcast mean wave direction during the Halloween storm of 1991 at NOAA buoy 44011 location.

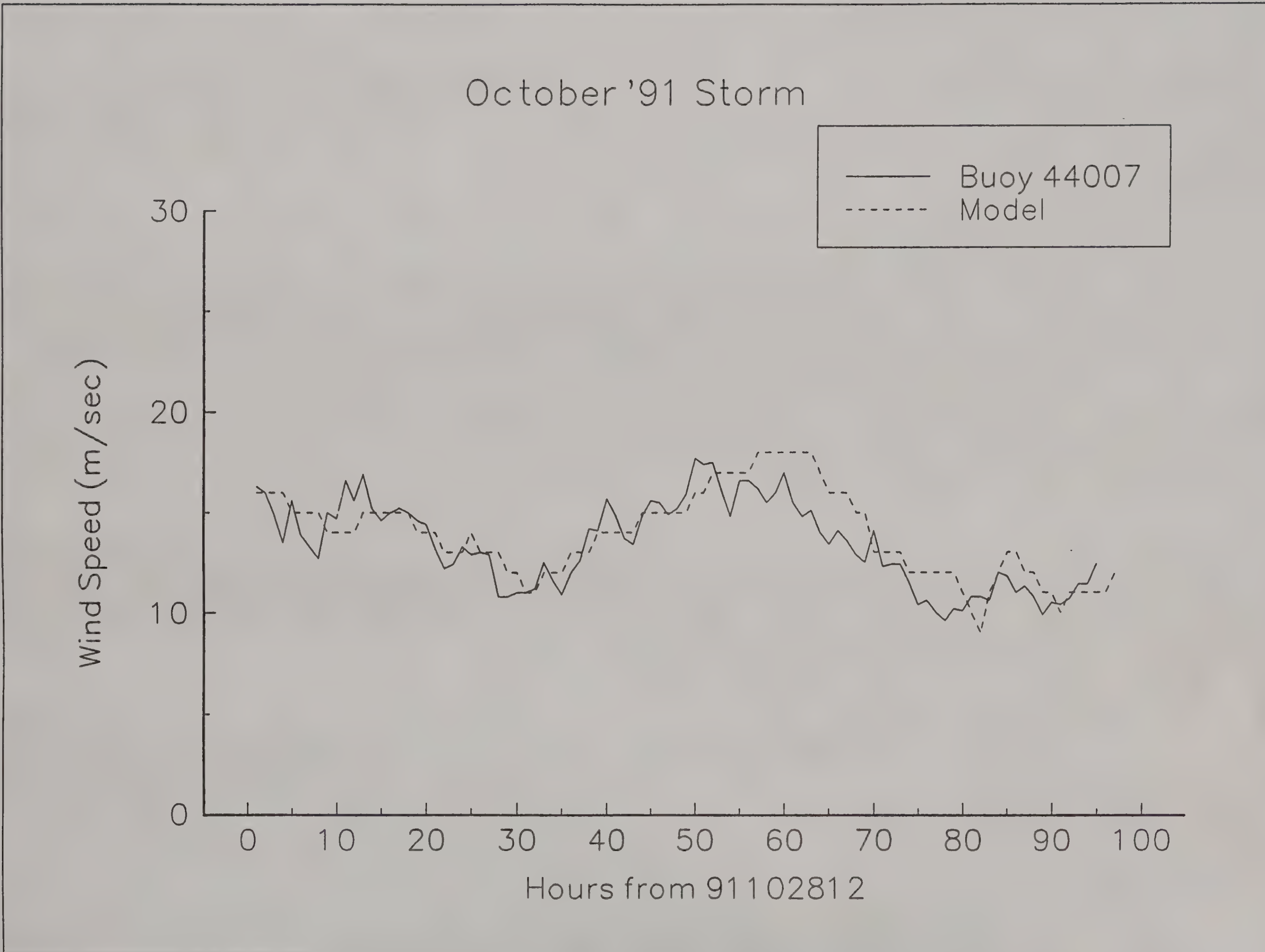


Figure 16. Measured and hindcast wind speed during the Halloween storm of 1991 at NOAA buoy 44007 location.

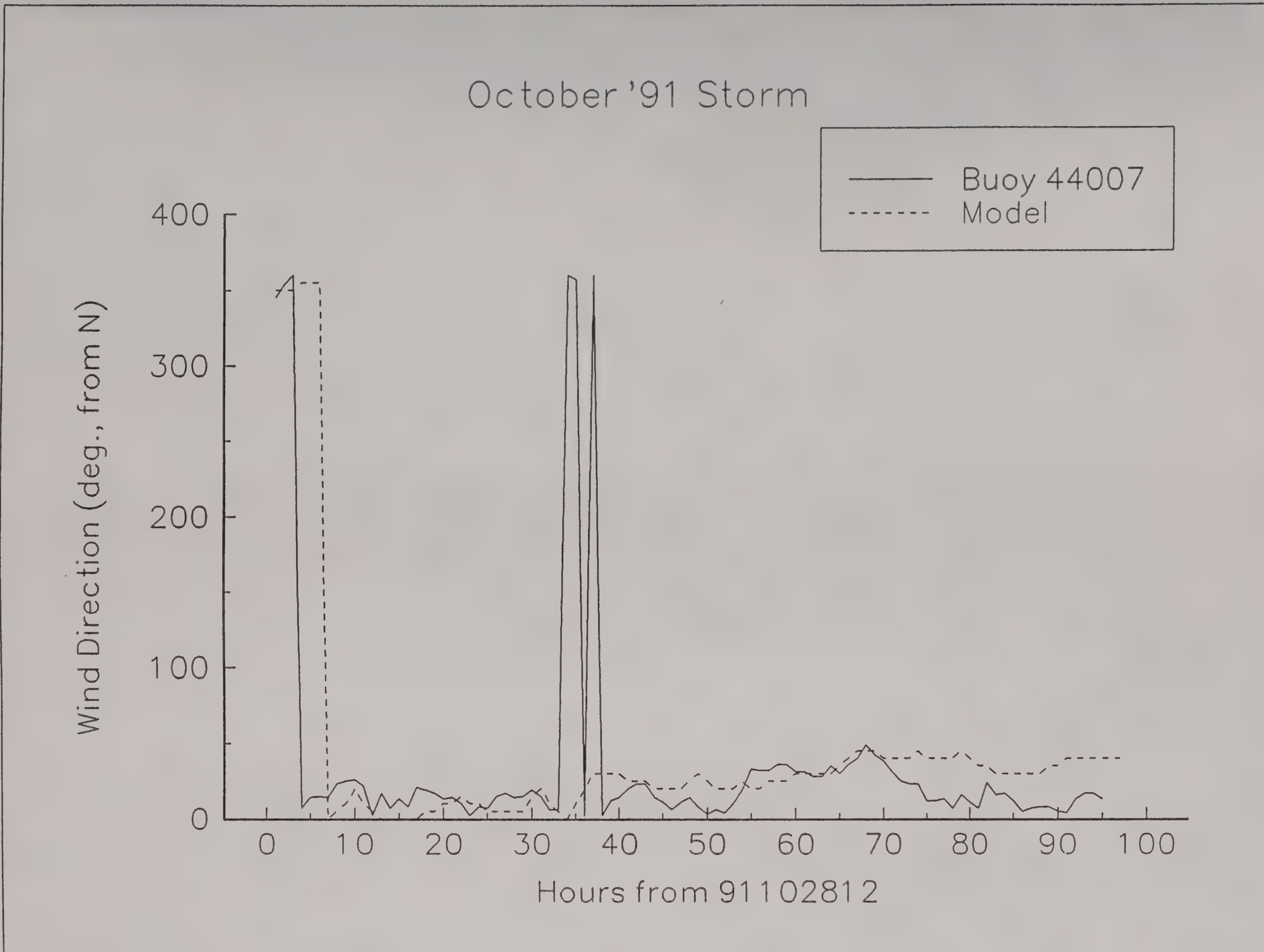


Figure 17. Measured and hindcast wind direction during the Halloween storm of 1991 at NOAA buoy 44007 location.

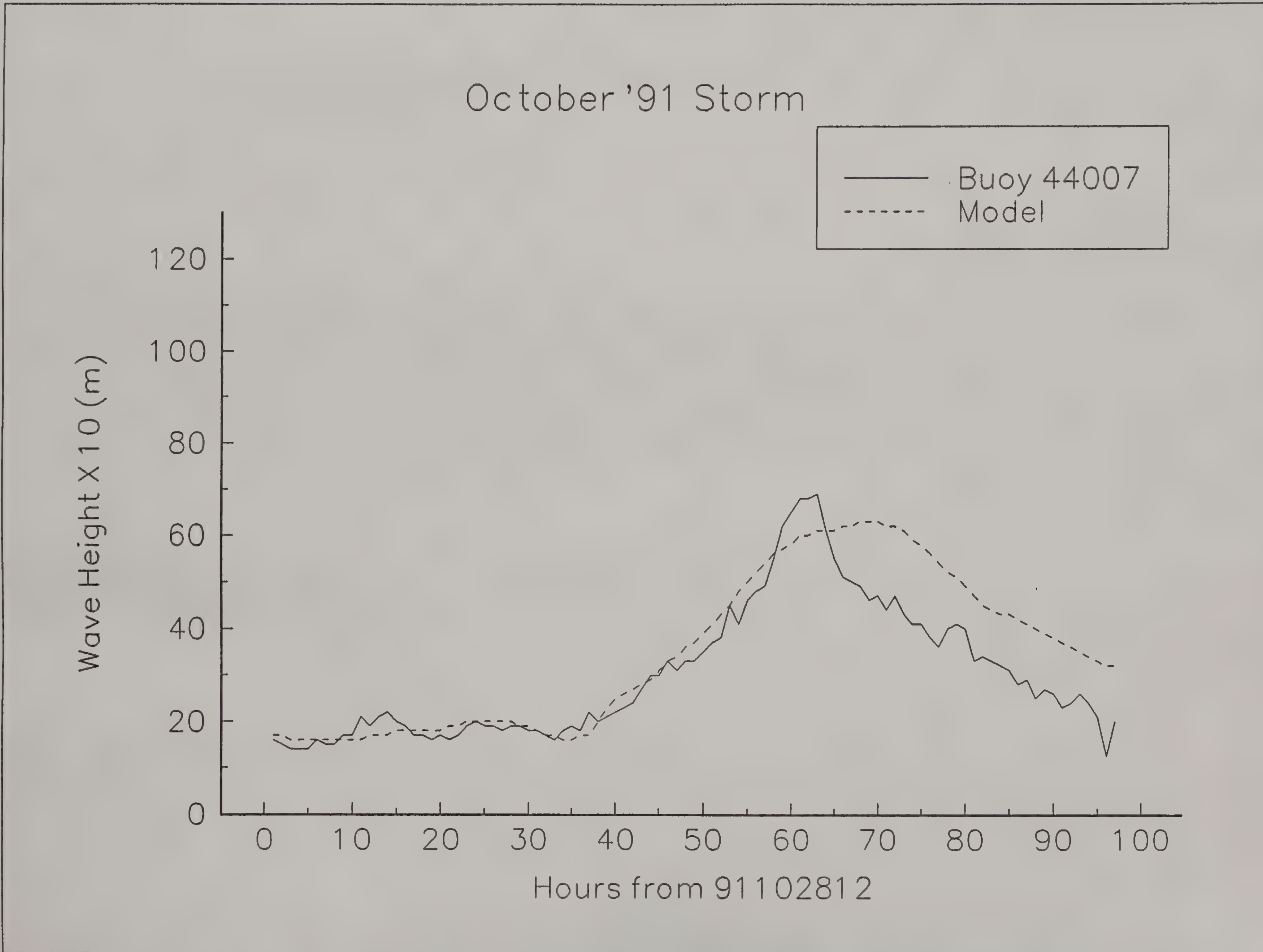
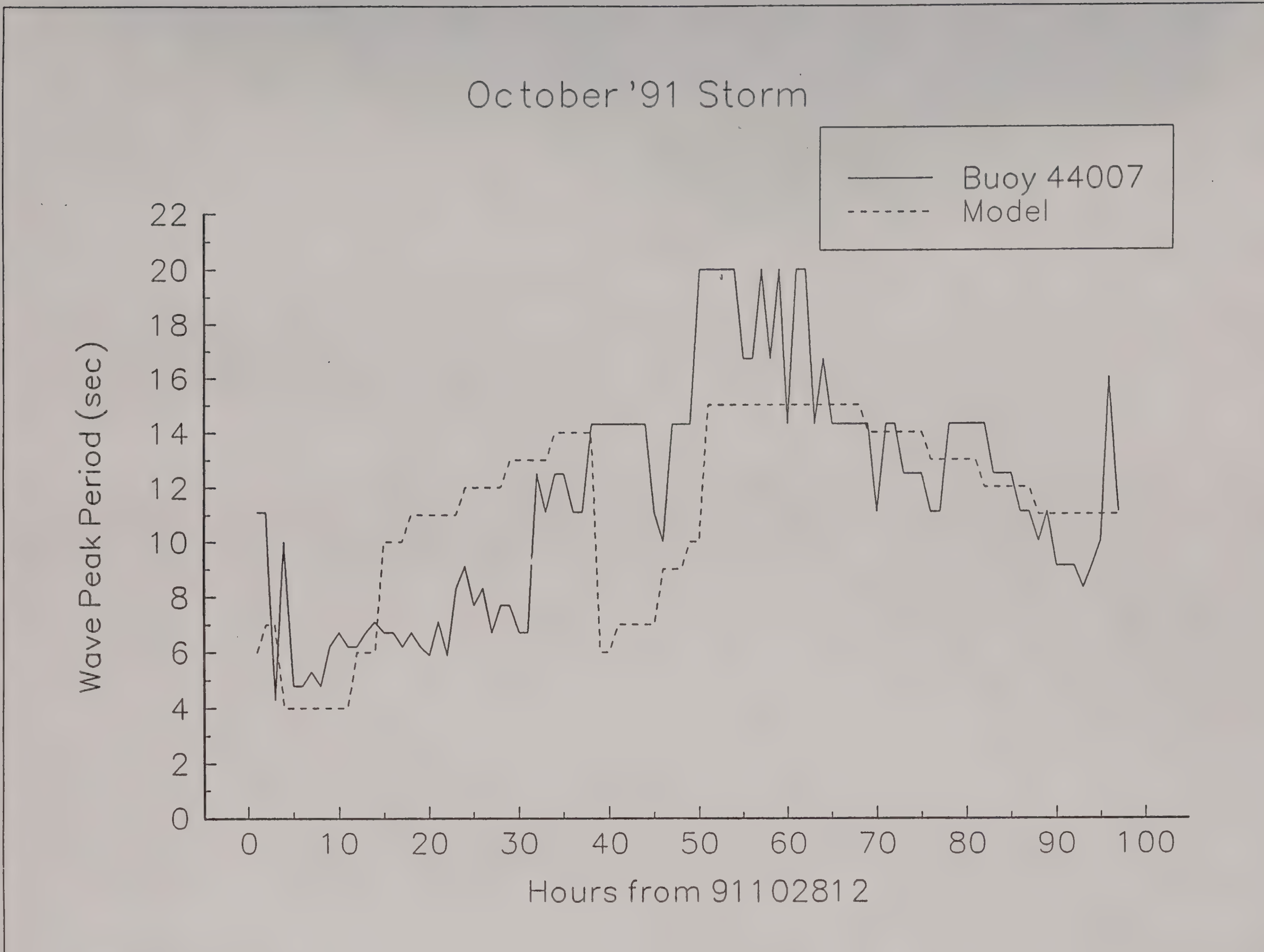


Figure 18. Measured and hindcast wave height during the Halloween storm of 1991 at NOAA buoy 44007 location.



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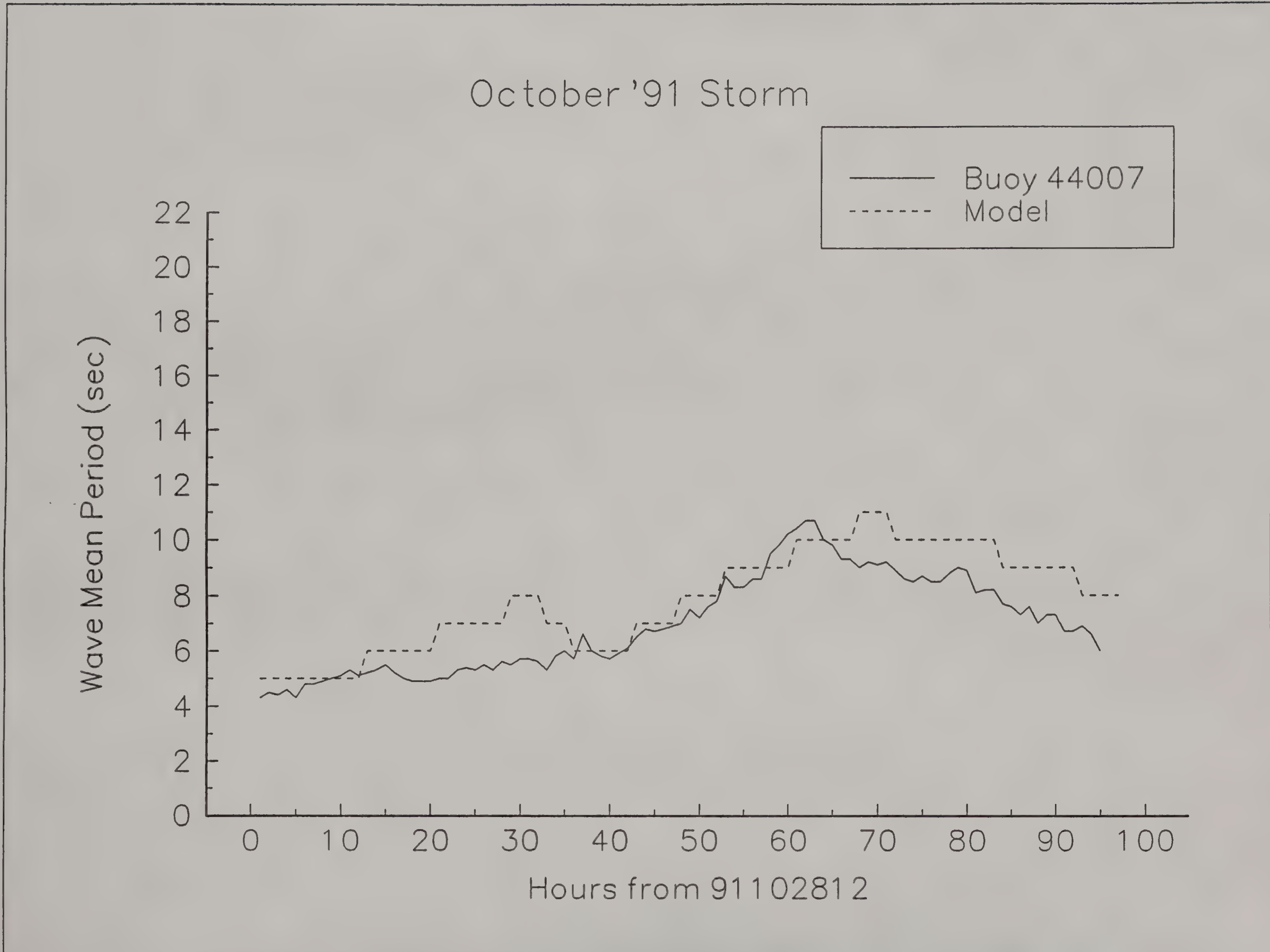

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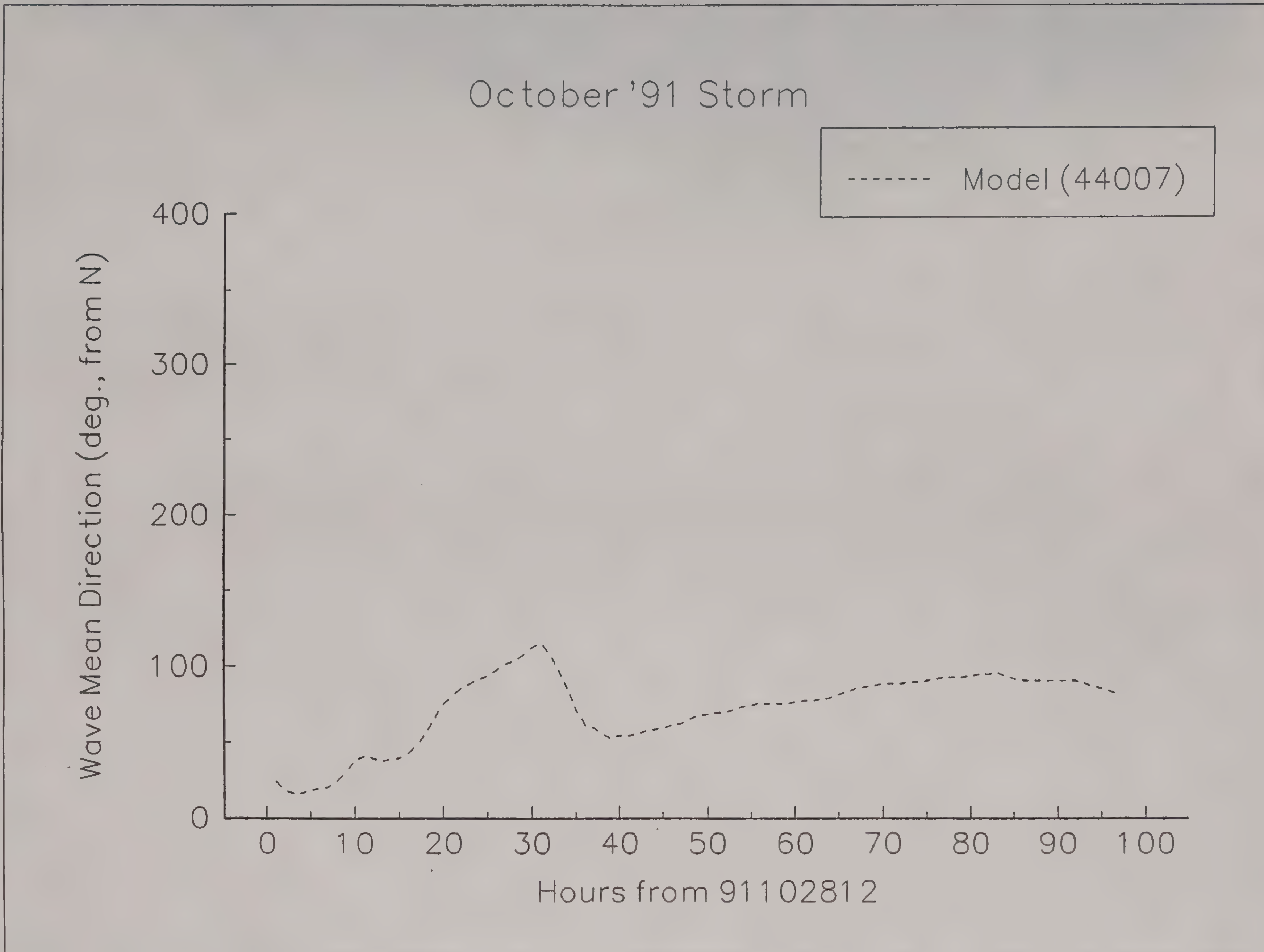


Figure 21. Hindcast mean wave direction during the Halloween storm of 1991 at NOAA buoy 44007 location.

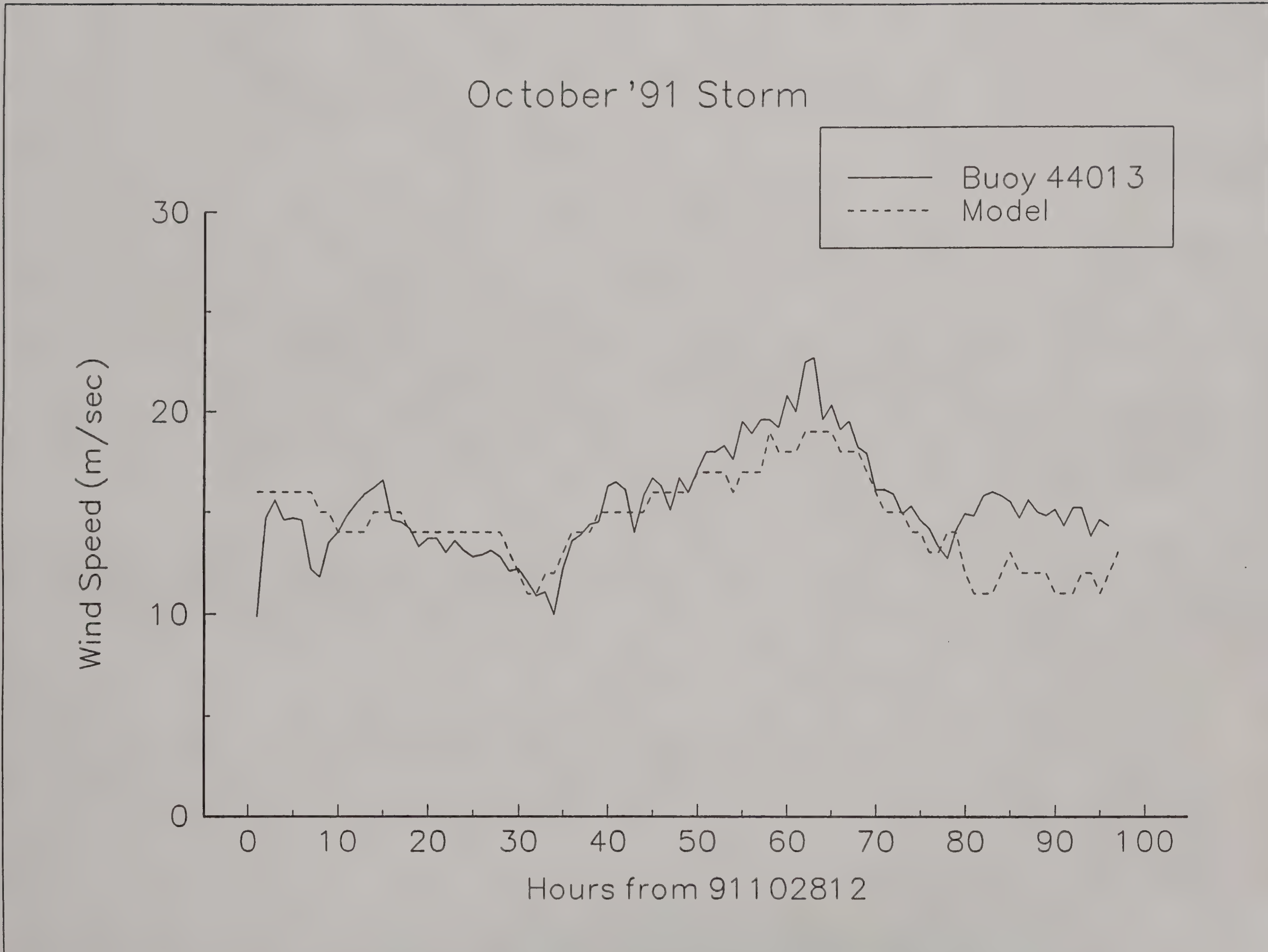


Figure 22. Measured and hindcast wind speed during the Halloween storm of 1991 at NOAA buoy 44013 location.

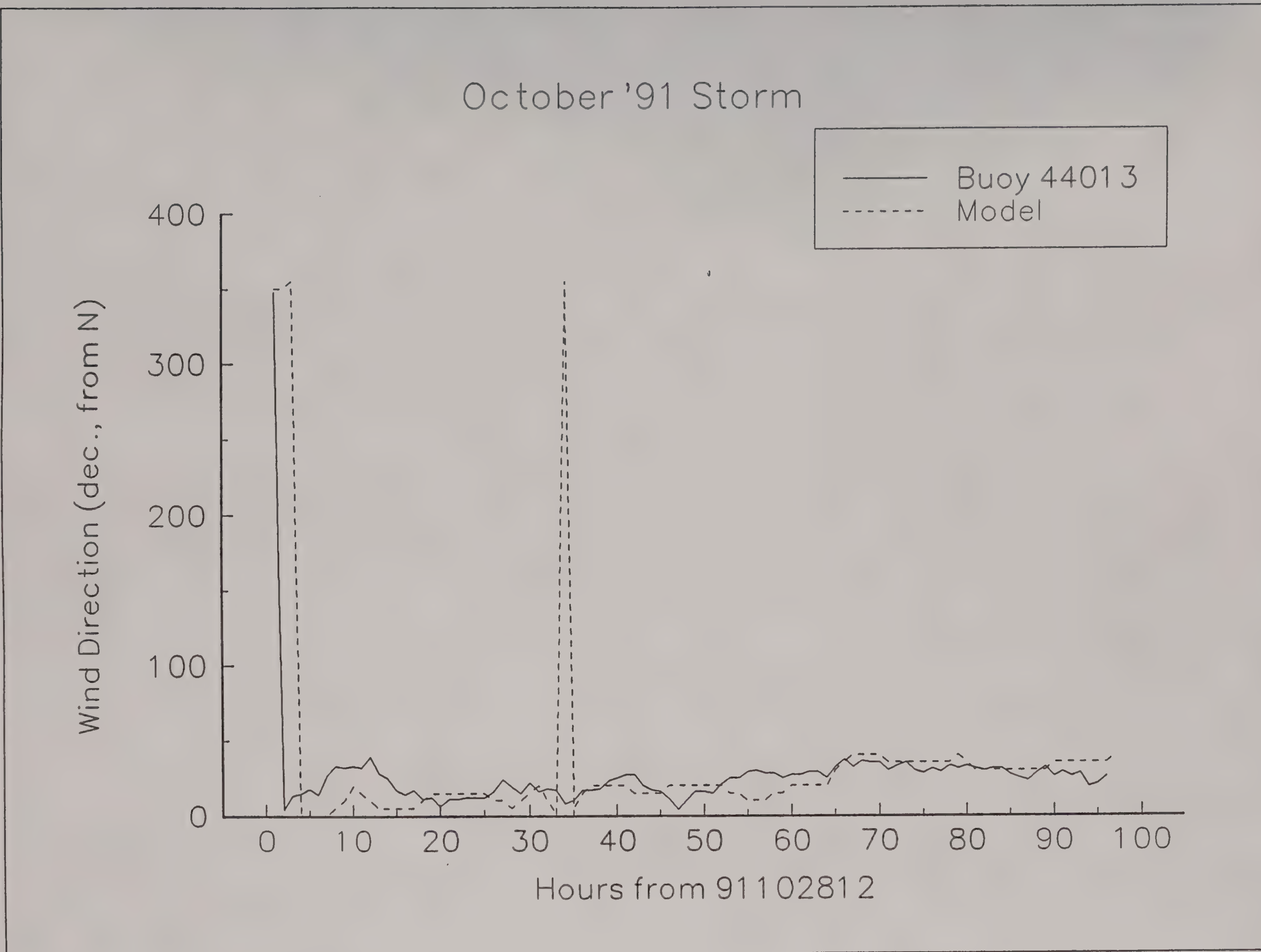


Figure 23. Measured and hindcast wind direction during the Halloween storm of 1991 at NOAA buoy 44013 location.

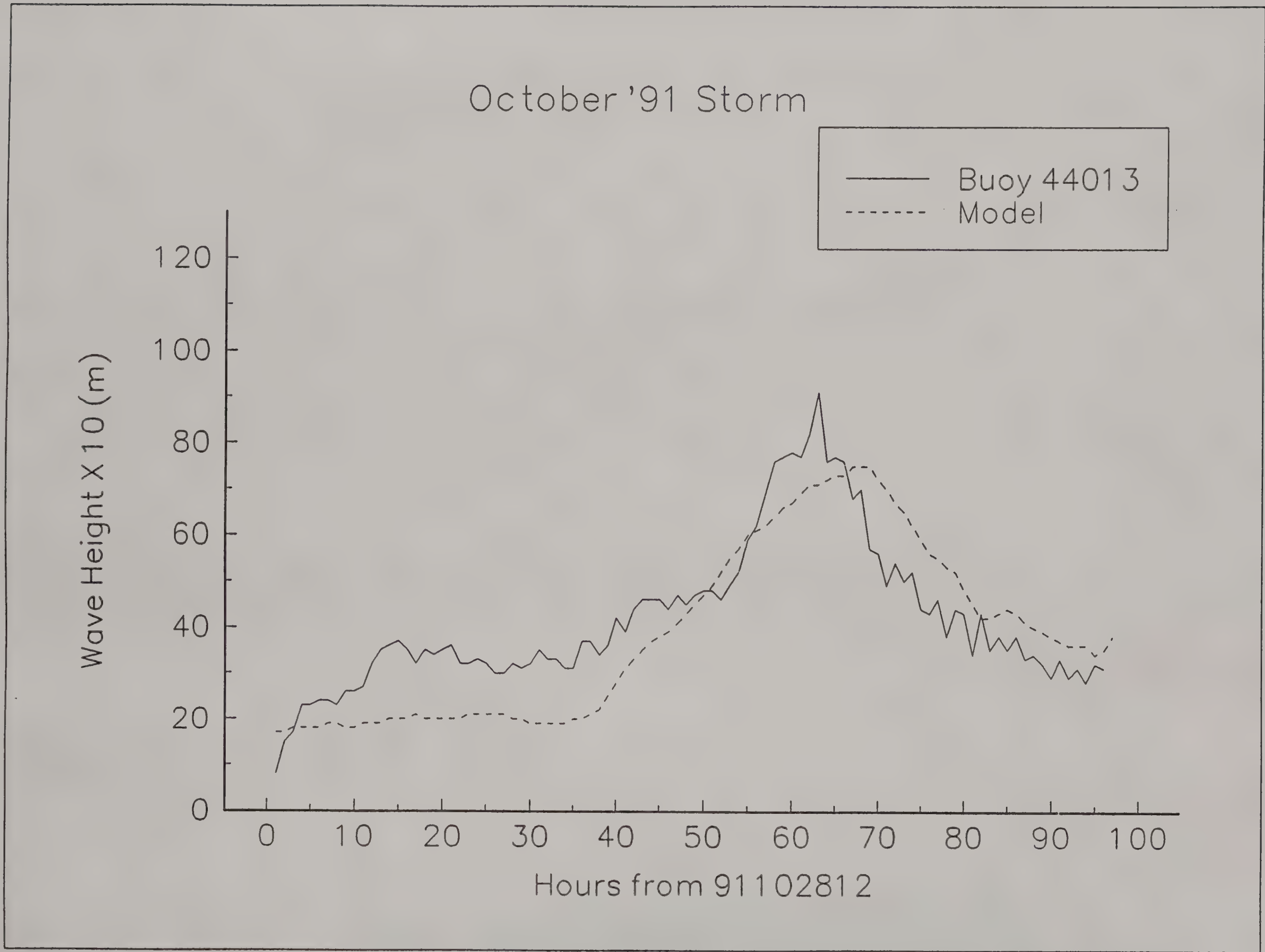
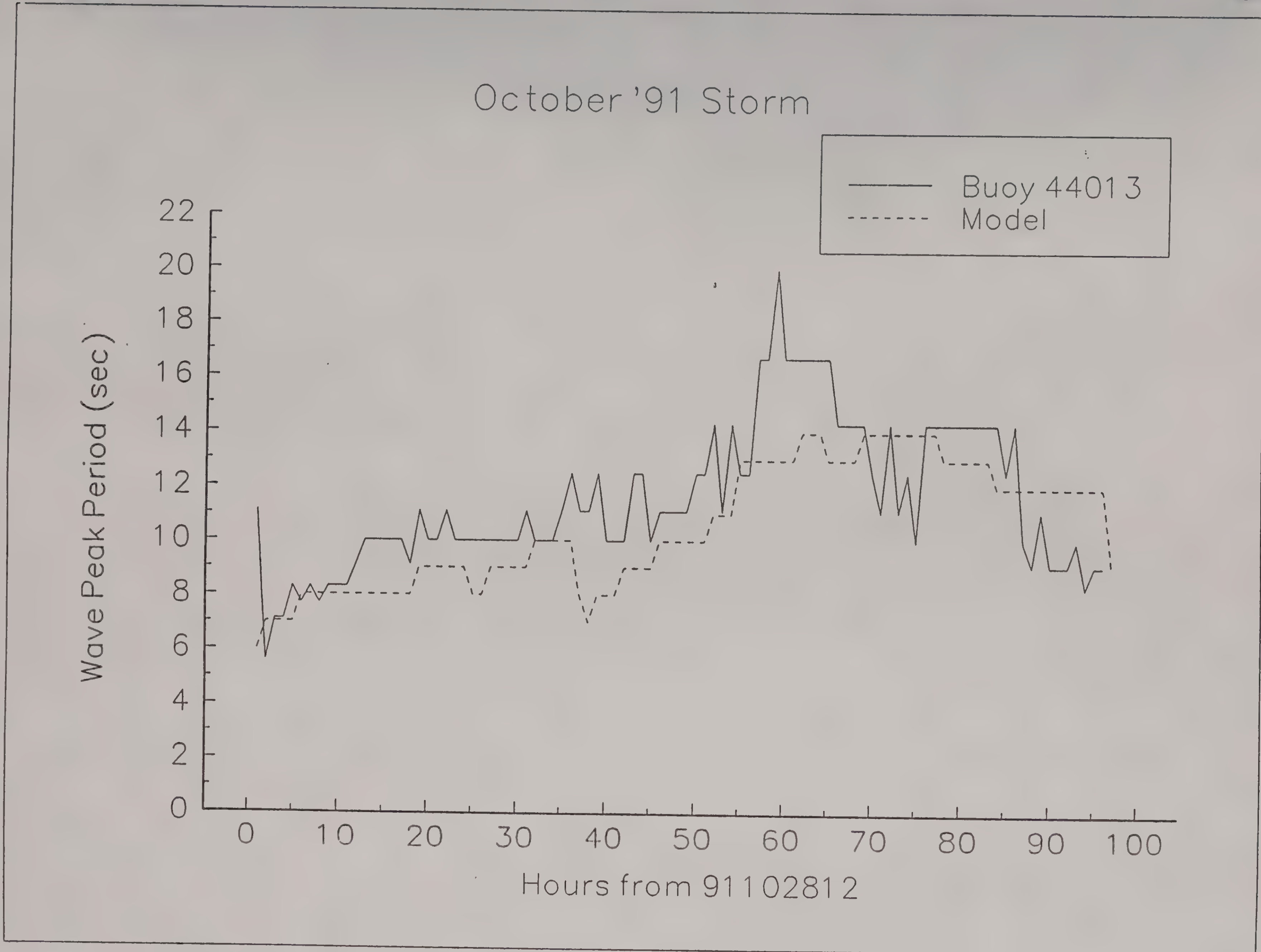


Figure 24. Measured and hindcast wave height during the Halloween storm of 1991 at NOAA buoy 44013 location.



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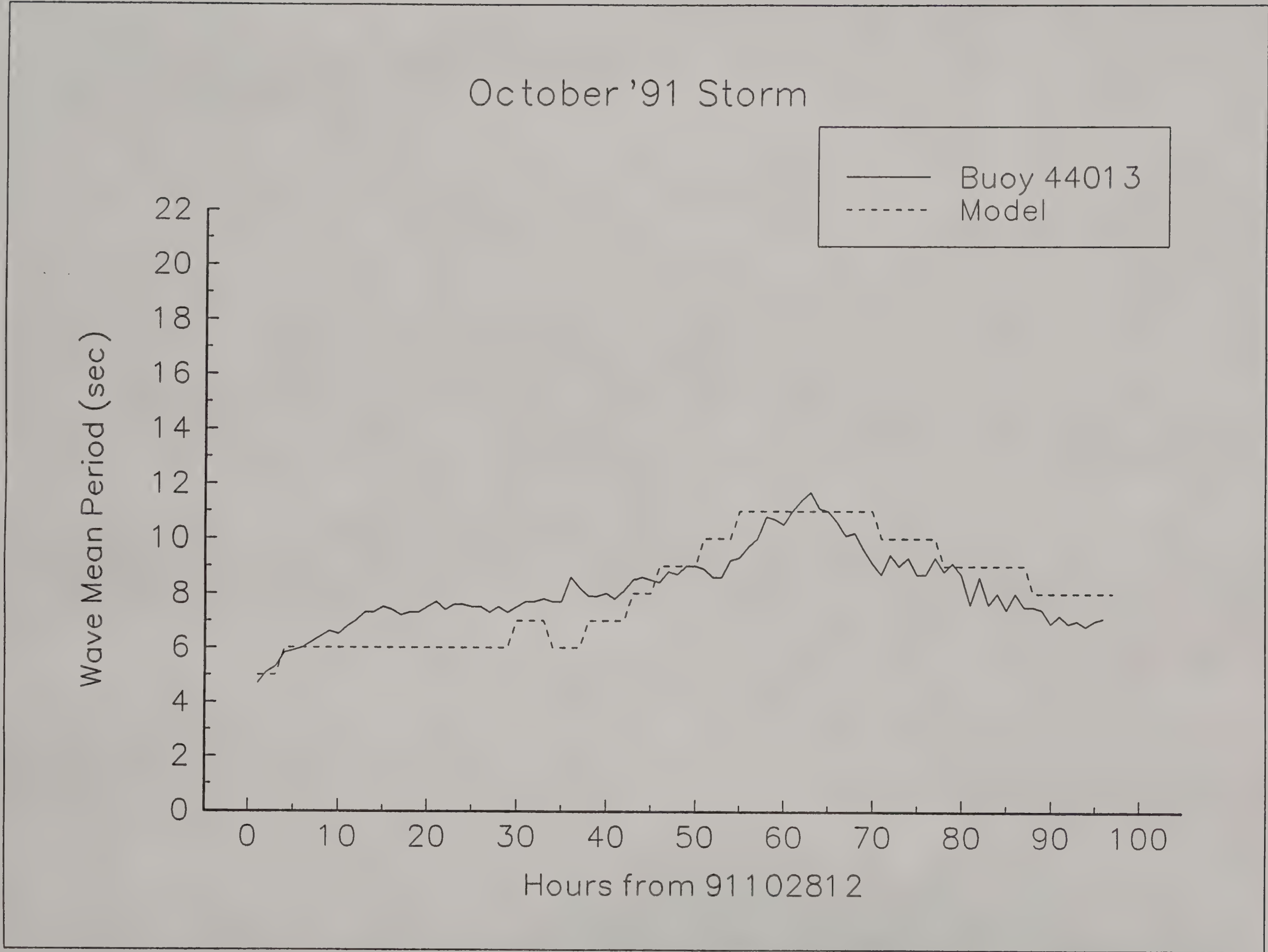


Figure 26. Measured and hindcast wave mean period during the Halloween storm of 1991 at NOAA buoy 44013 location.

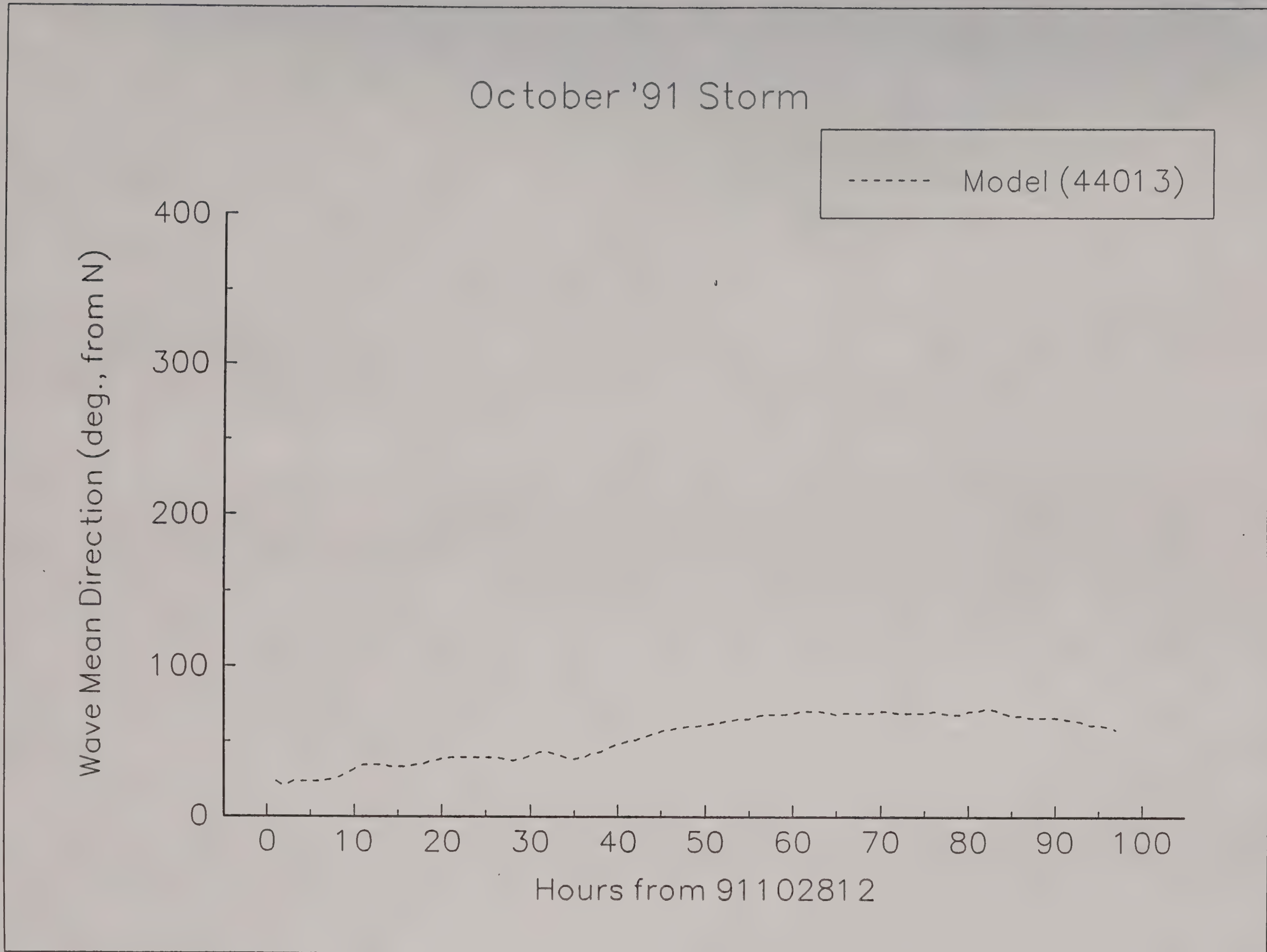


Figure 27. Hindcast mean wave direction during the Halloween storm of 1991 at NOAA buoy 44013 location.

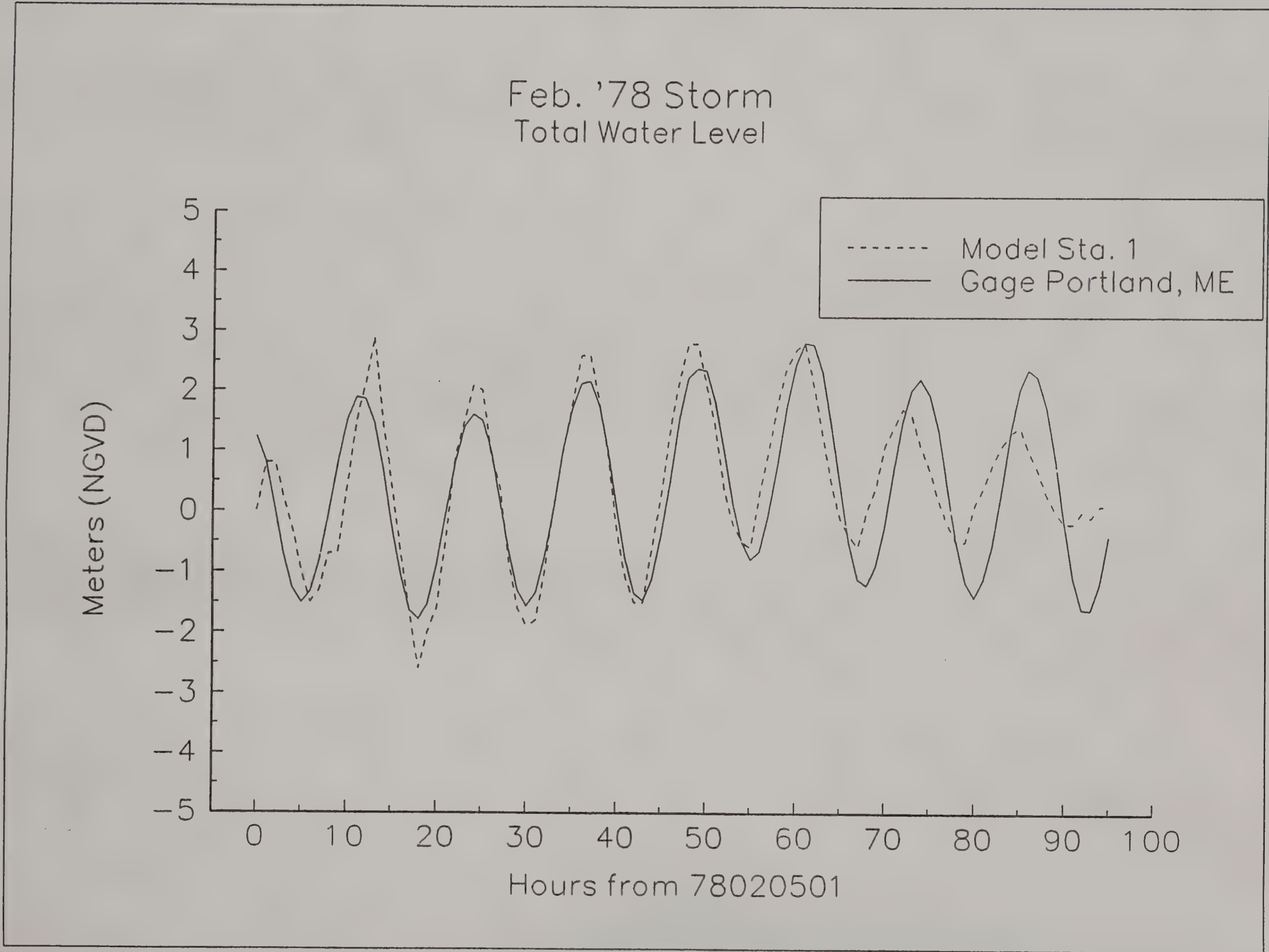
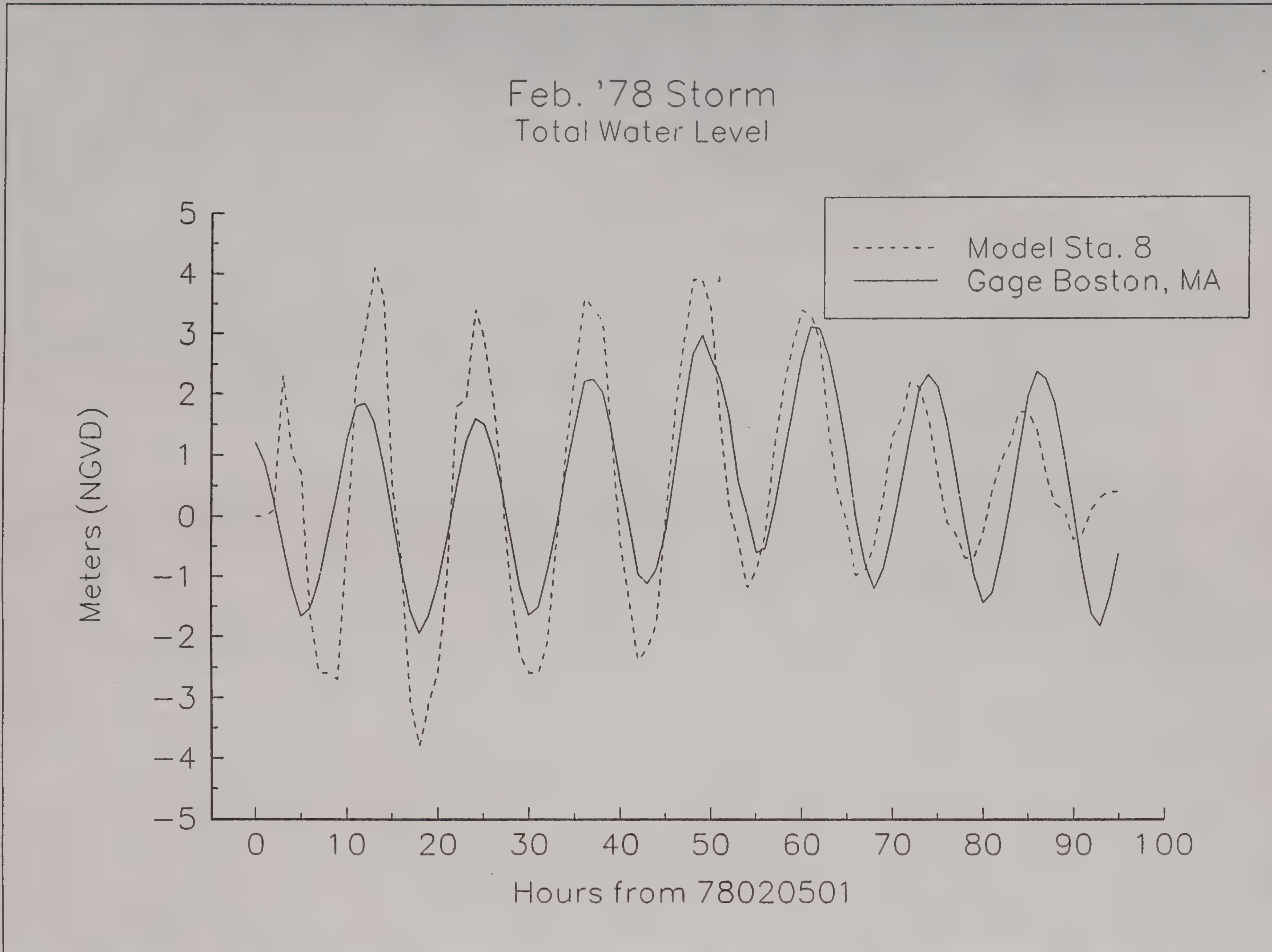


Figure 28. Measured and hindcast water level during the Blizzard of 1978 at Portland, ME tide gage and Station 1 respectively.



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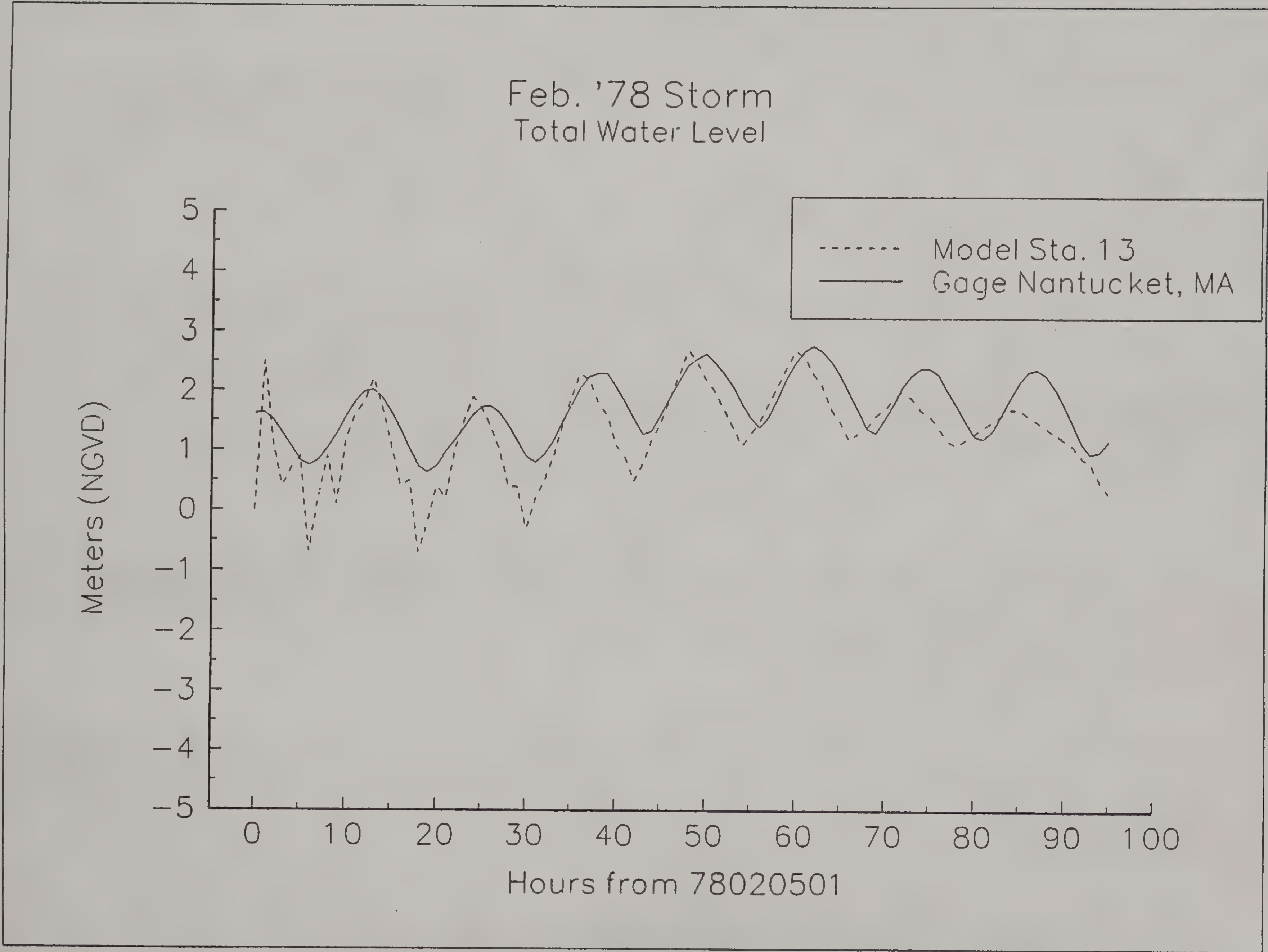

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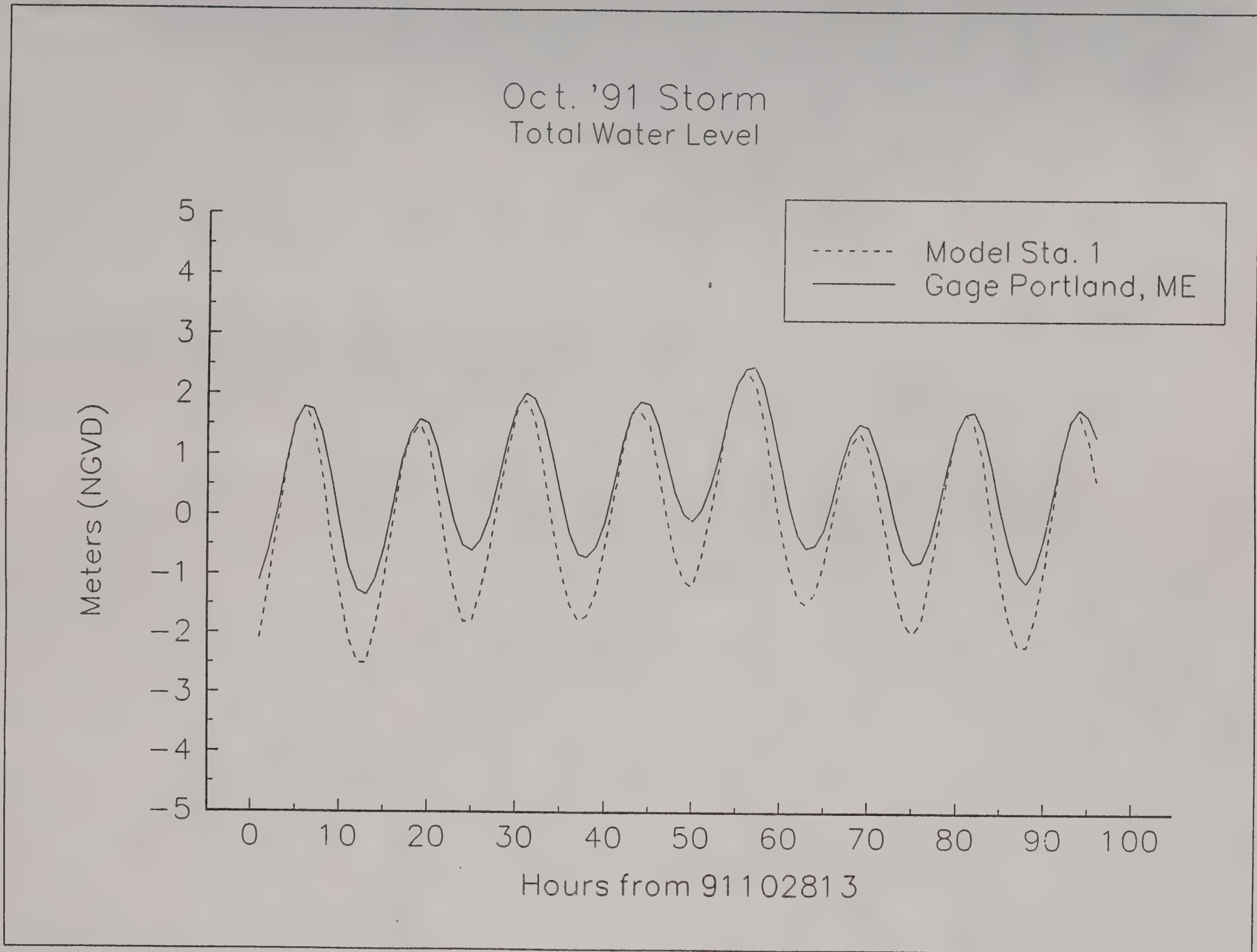

Figure 31. Measured and hindcast water level during the Halloween storm of 1991 at Portland, ME tide gage and Station 1 respectively.

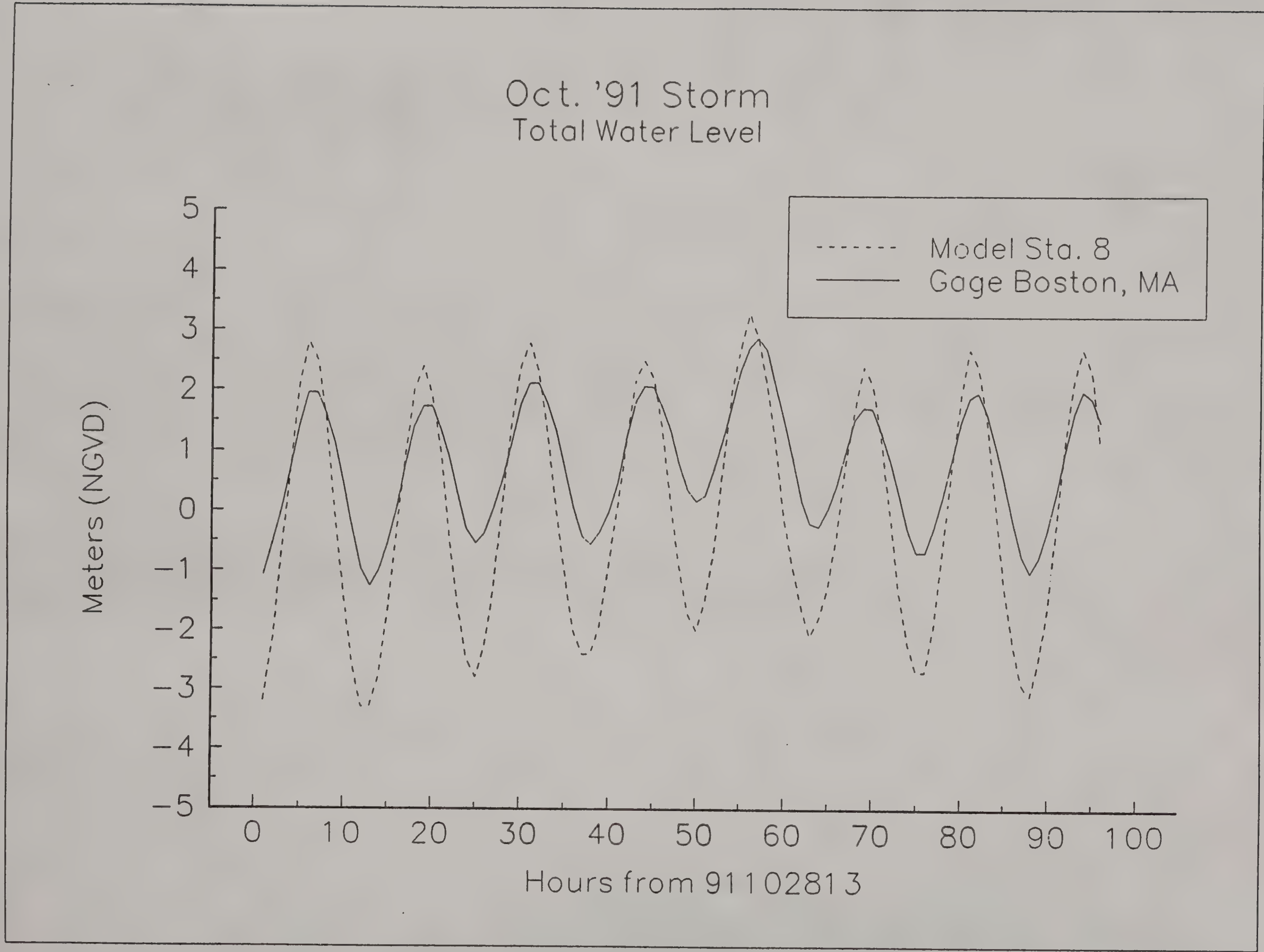

Figure 32. Measured and hindcast water level during the Halloween storm of 1991 at Boston, MA tide gage and Station 8 respectively.

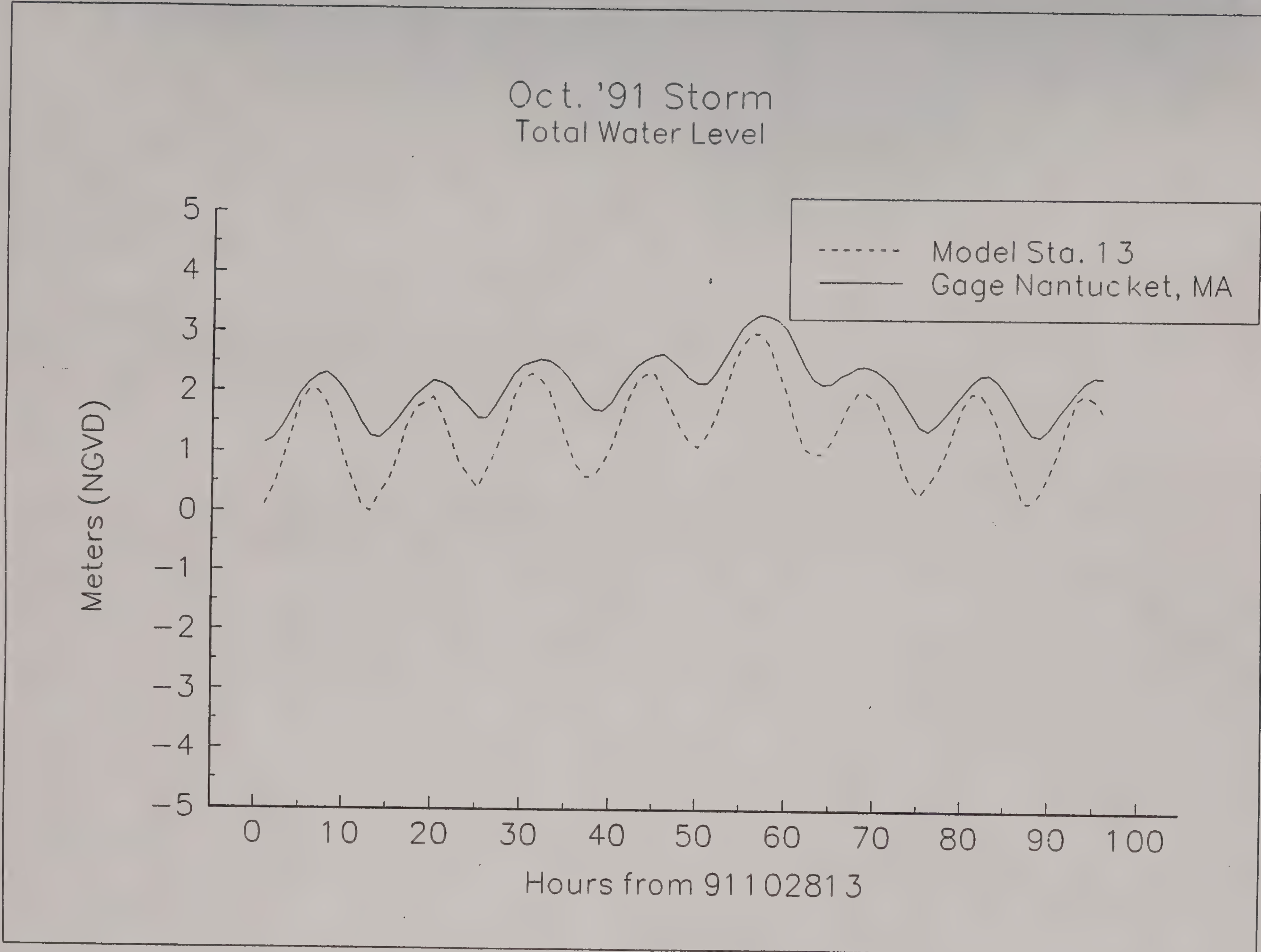

Figure 33. Measured and hindcast water level during the Halloween storm of 1991 at Nantucket, MA tide gage and Station 13 respectively.

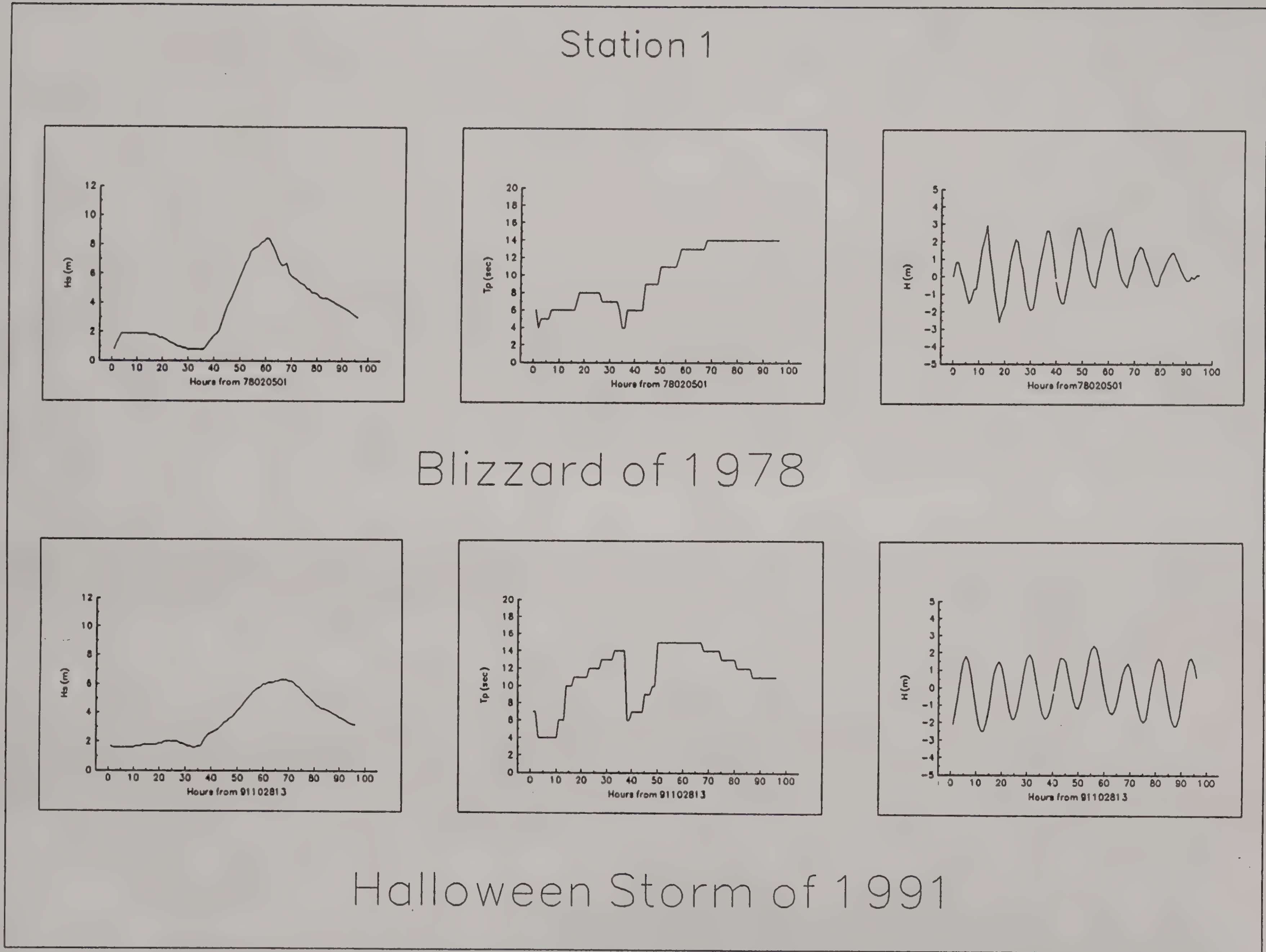

Figure 34. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 1.

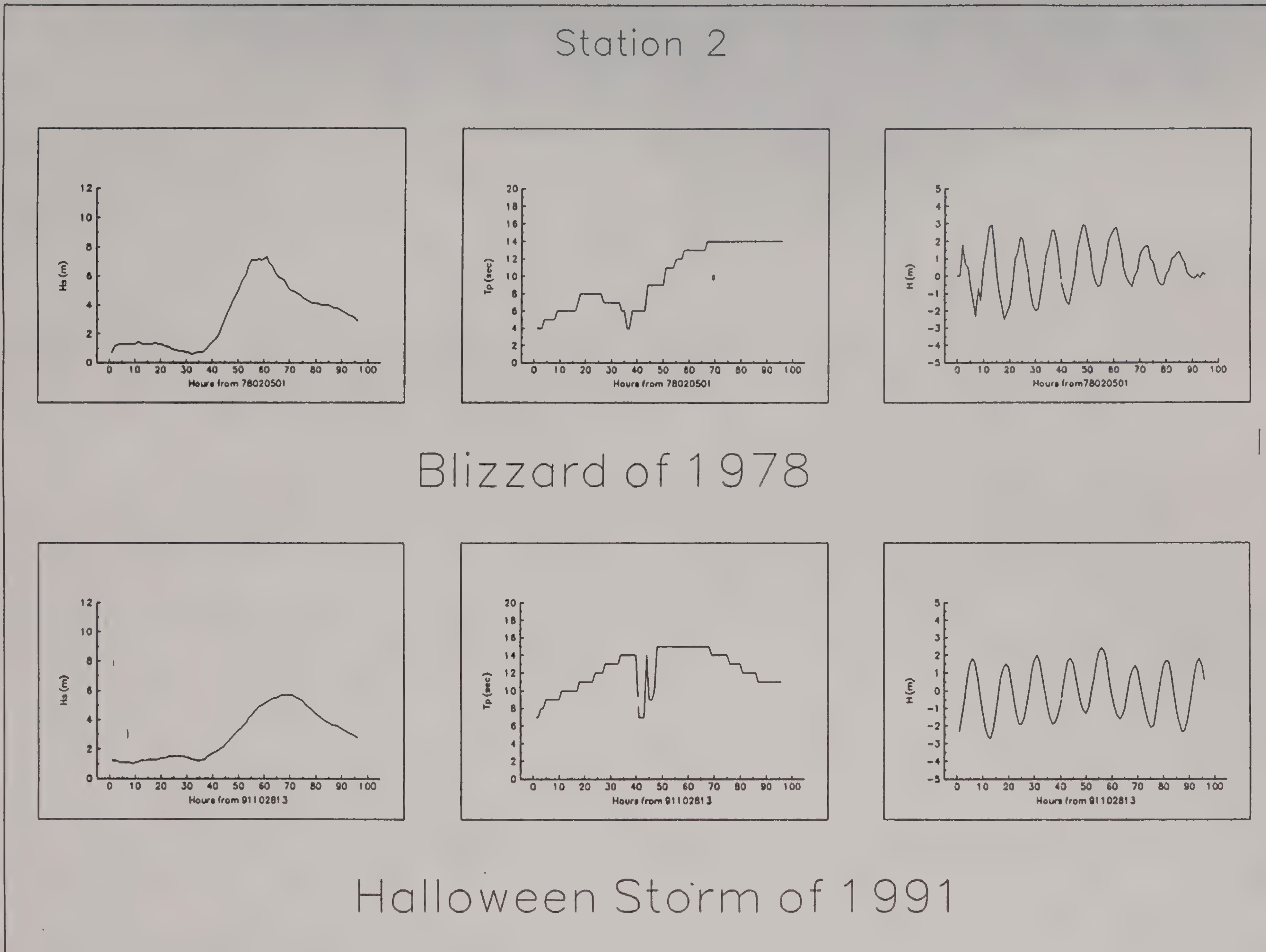

Figure 35. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 2.

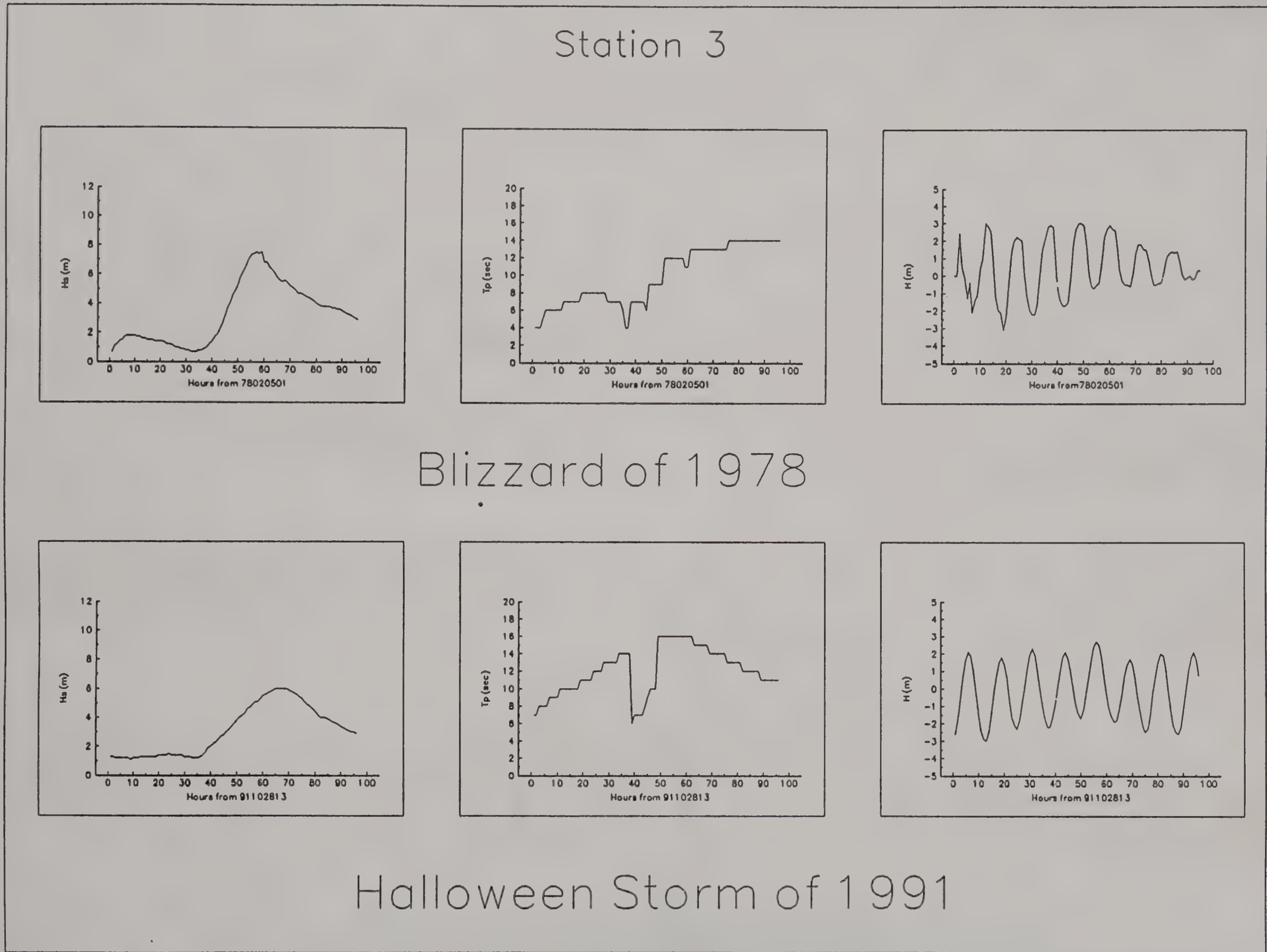

Figure 36. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 3.

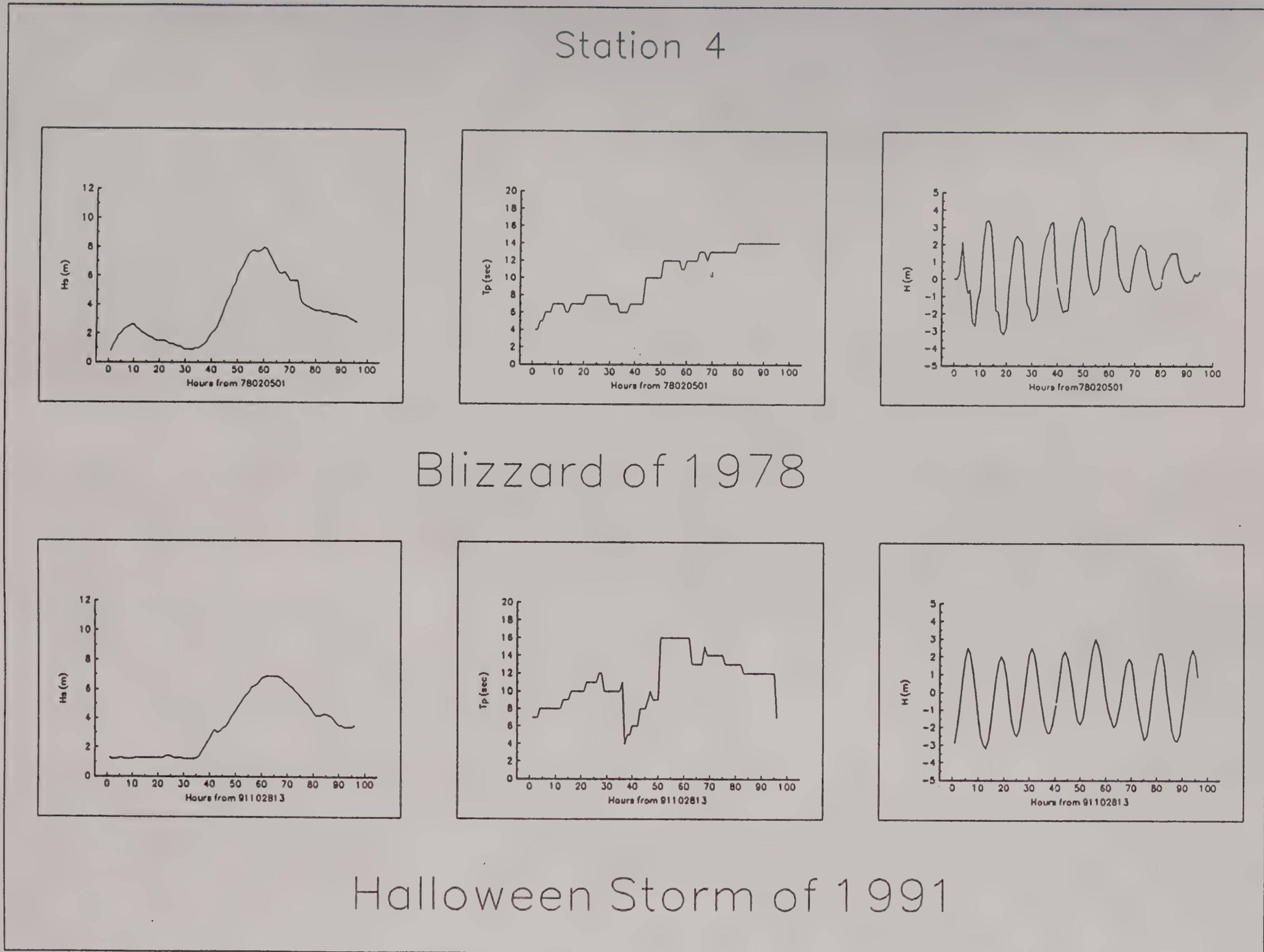

Figure 37. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 4.

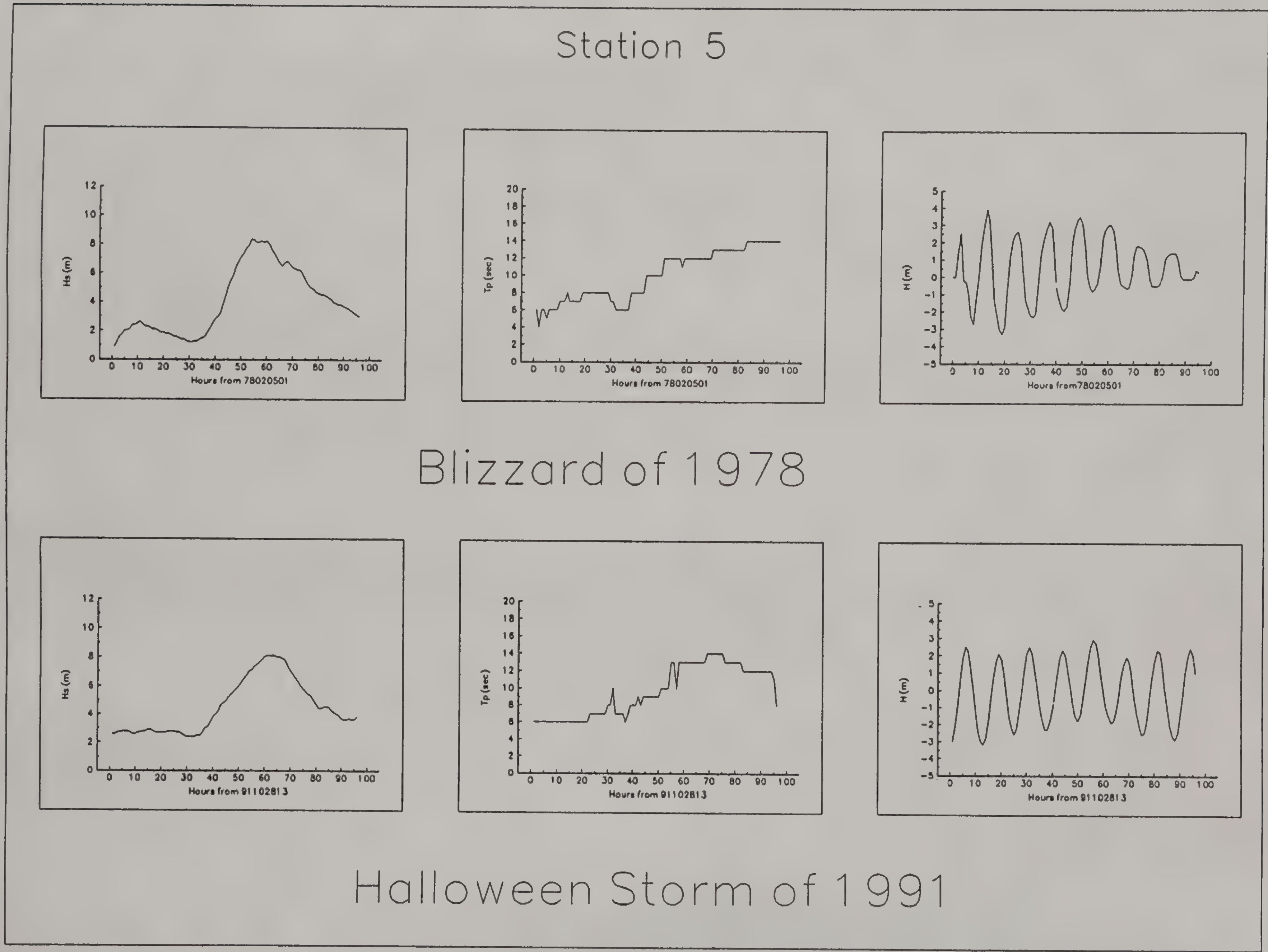

Figure 38. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 5.

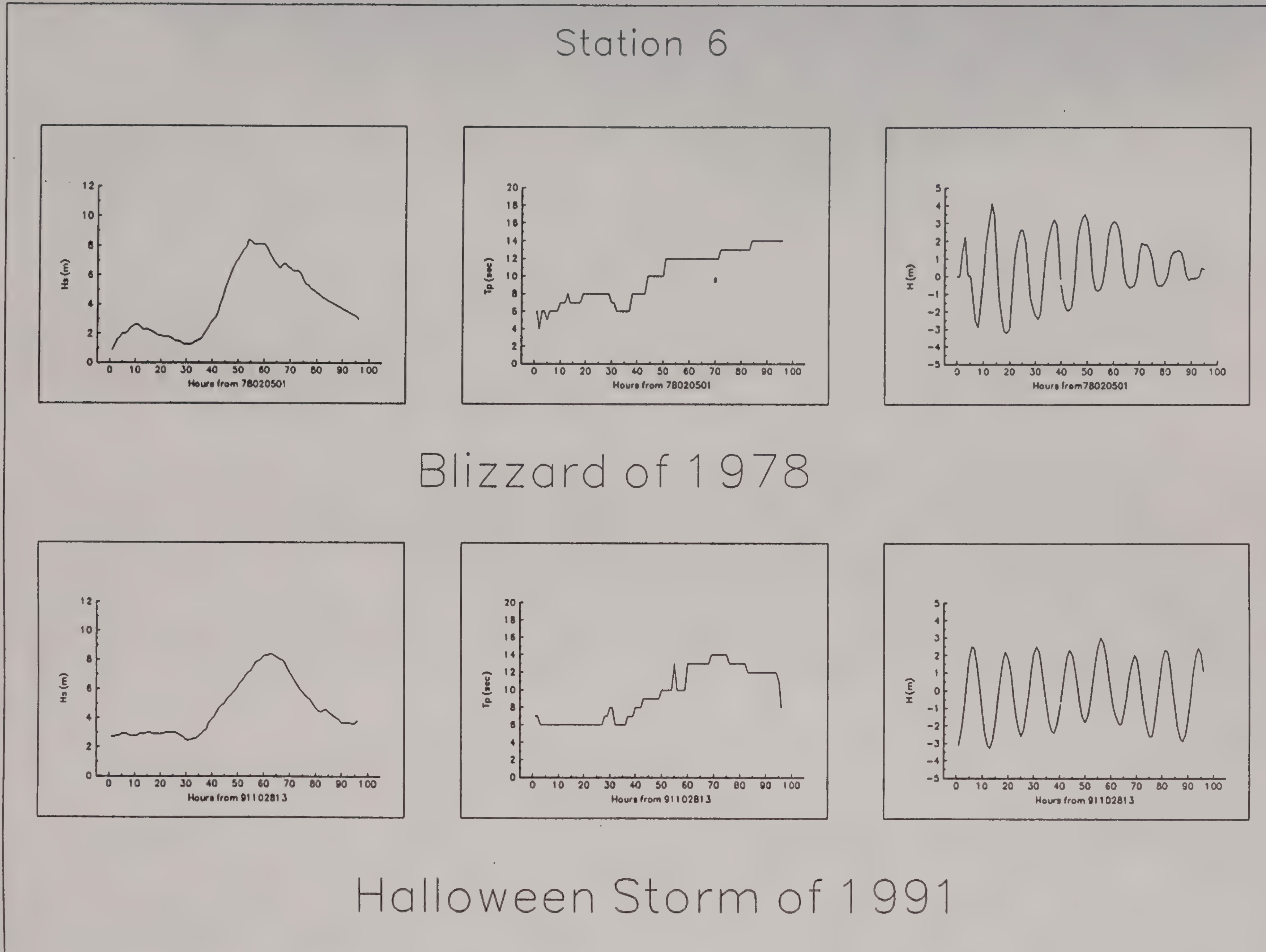

Figure 39. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 6.

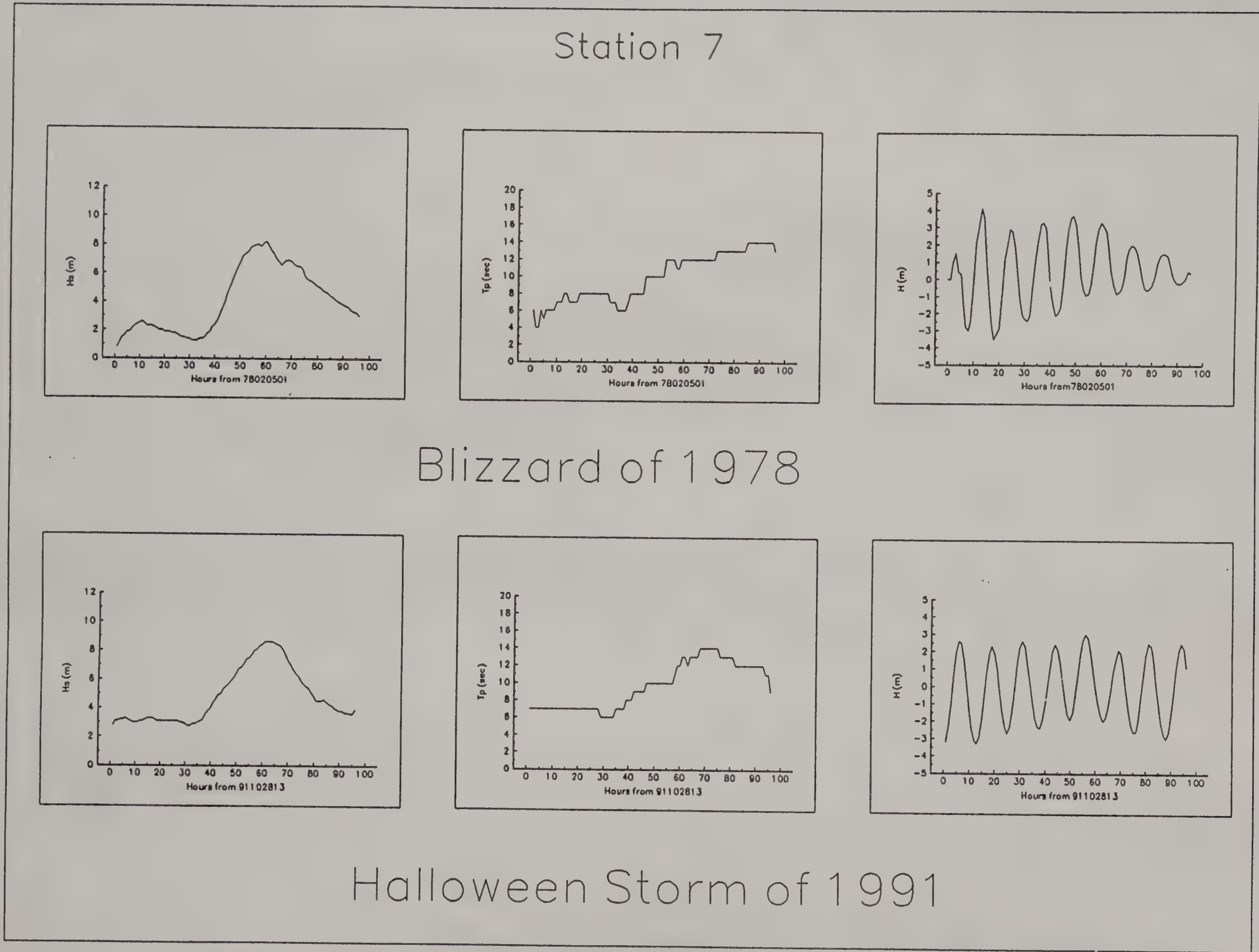

Figure 40. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 7.

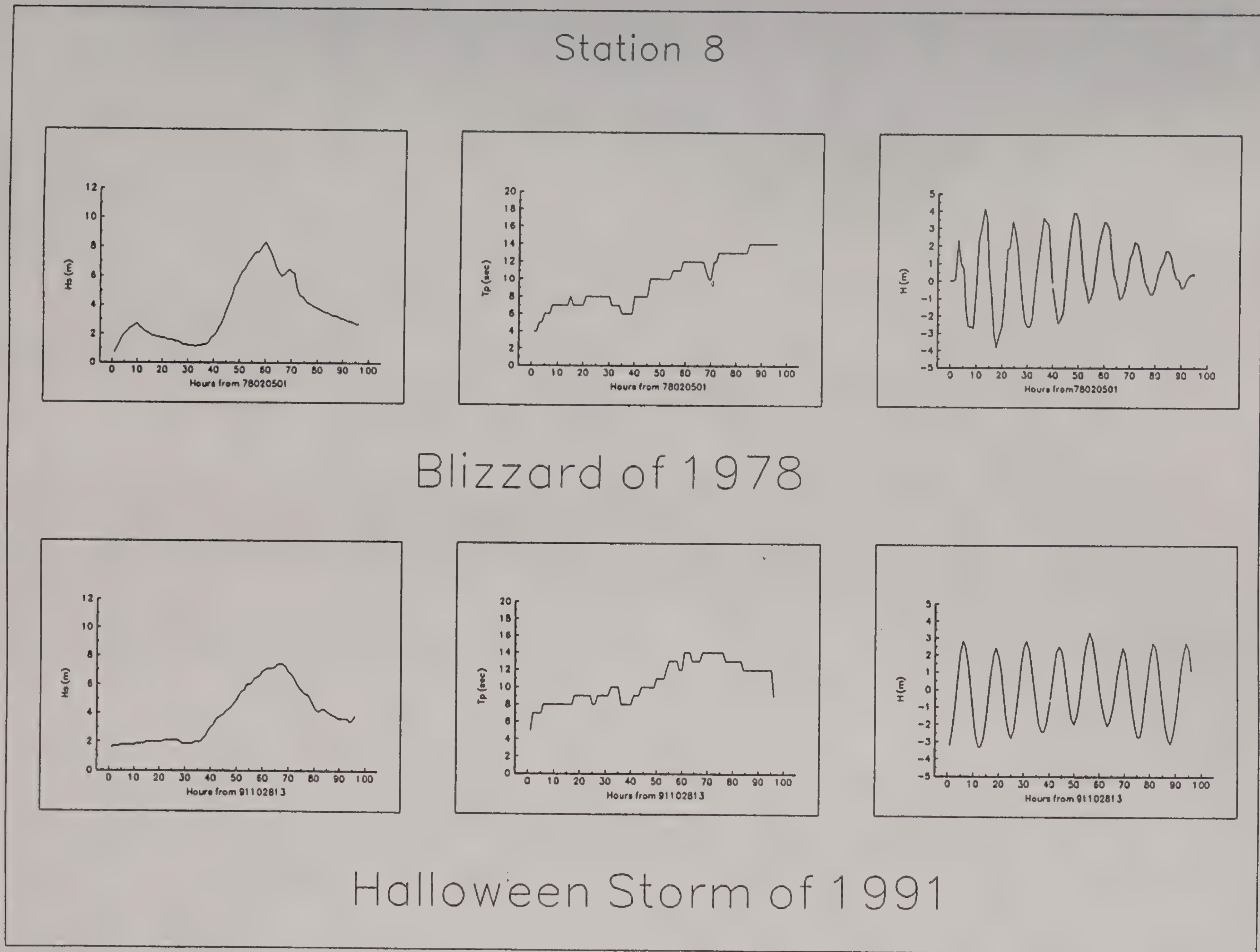

Figure 41. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 8.

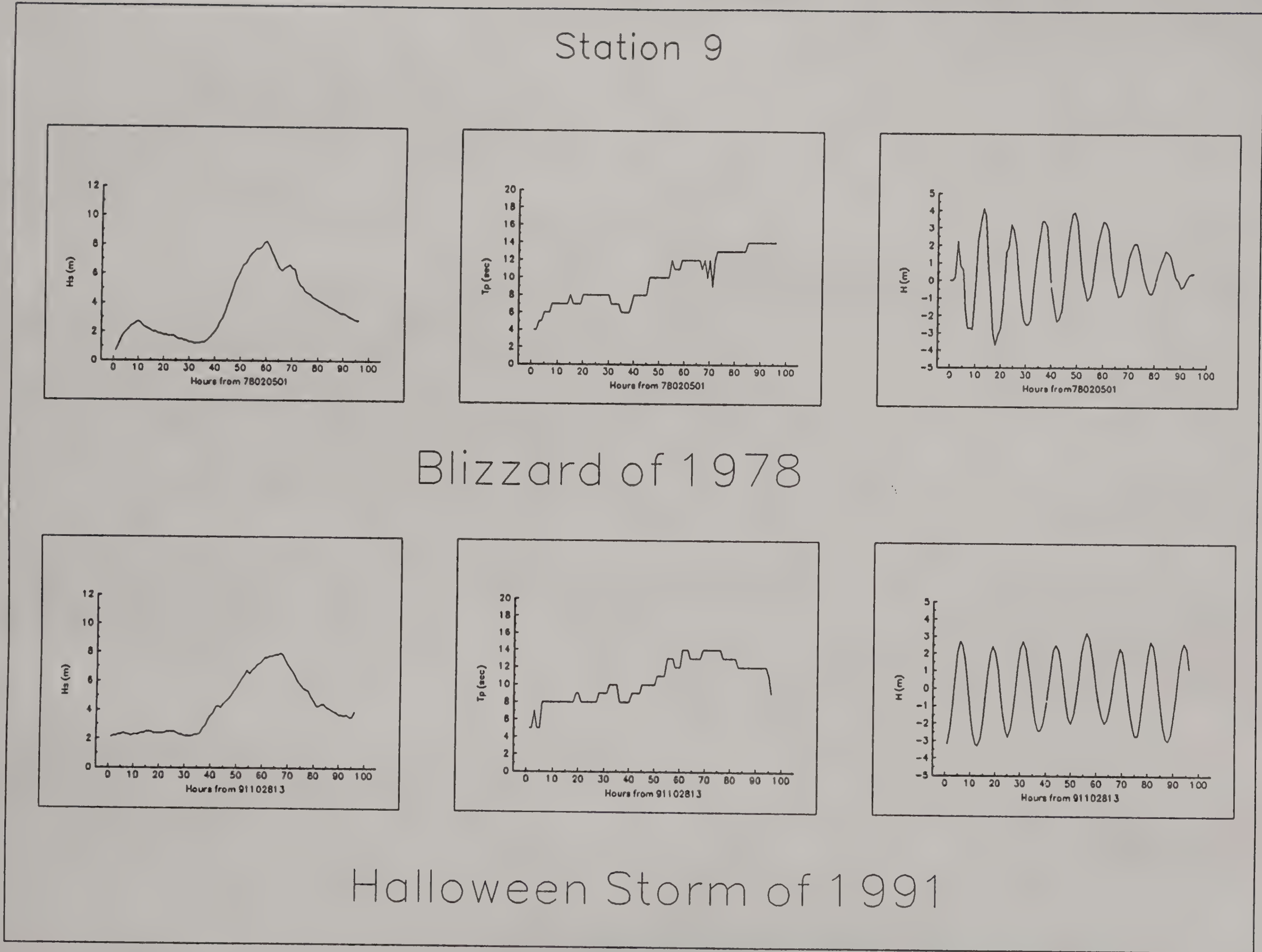

Figure 42. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 9.

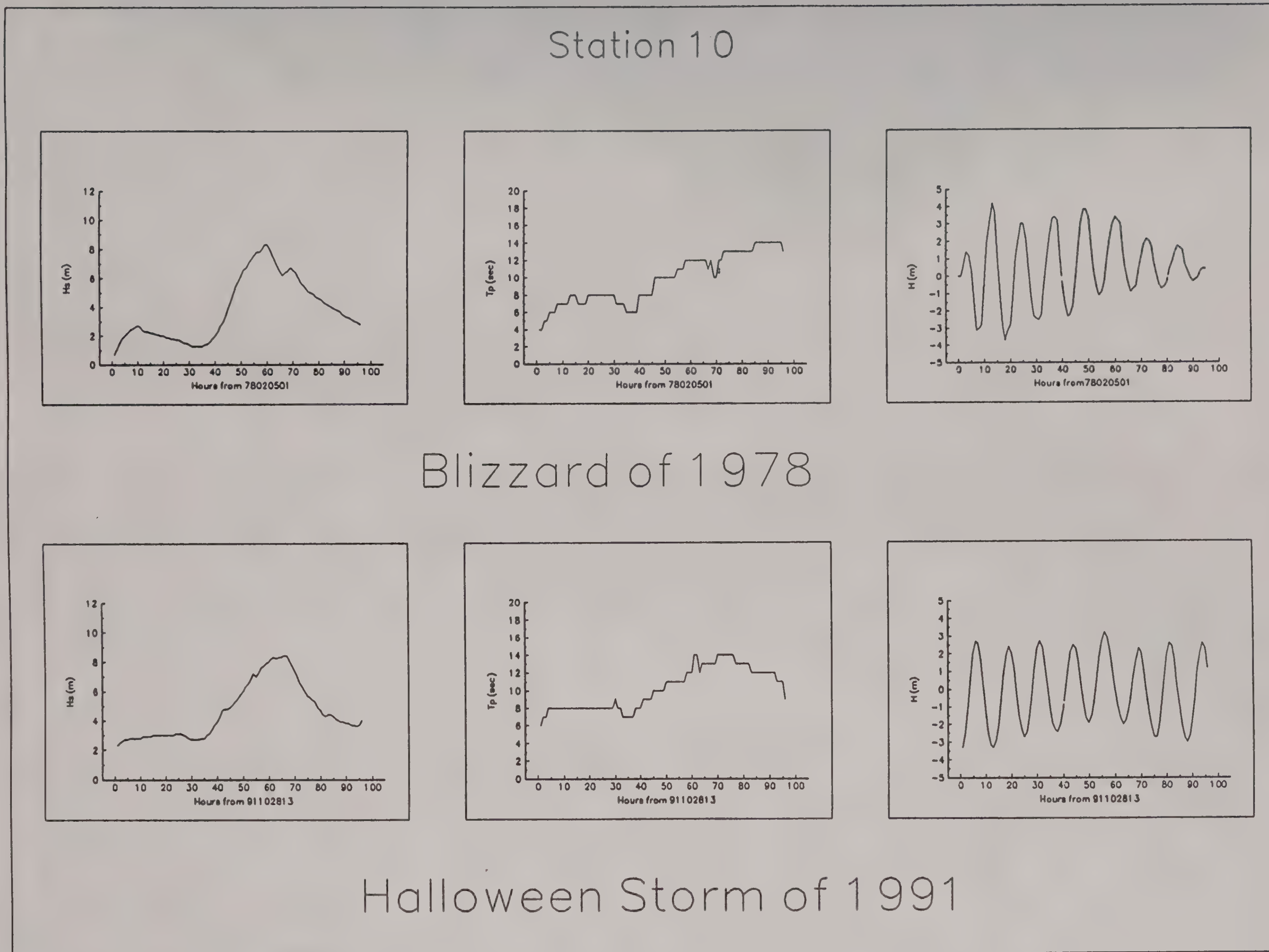

Figure 43. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 10.

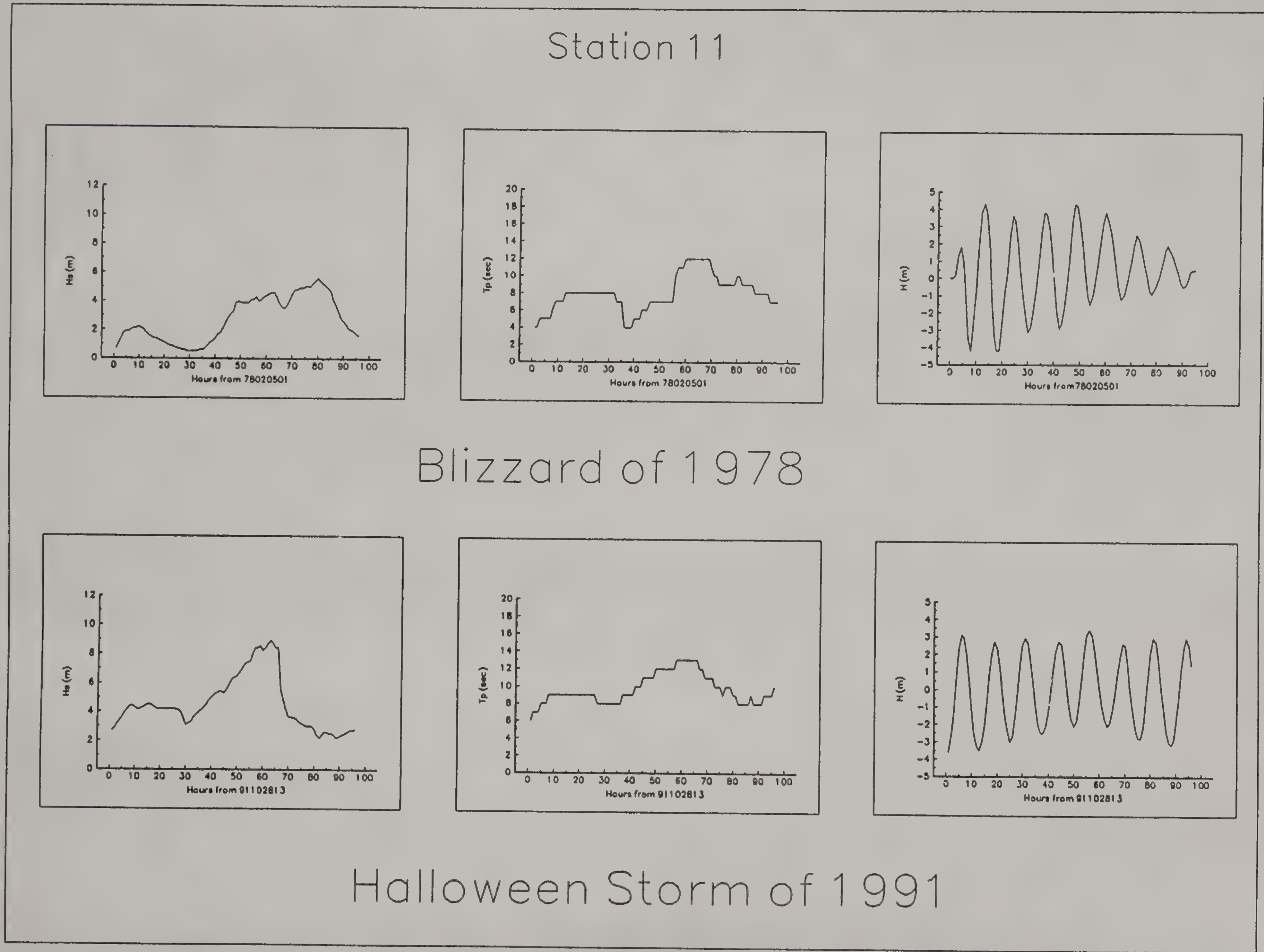

Figure 44. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 11.

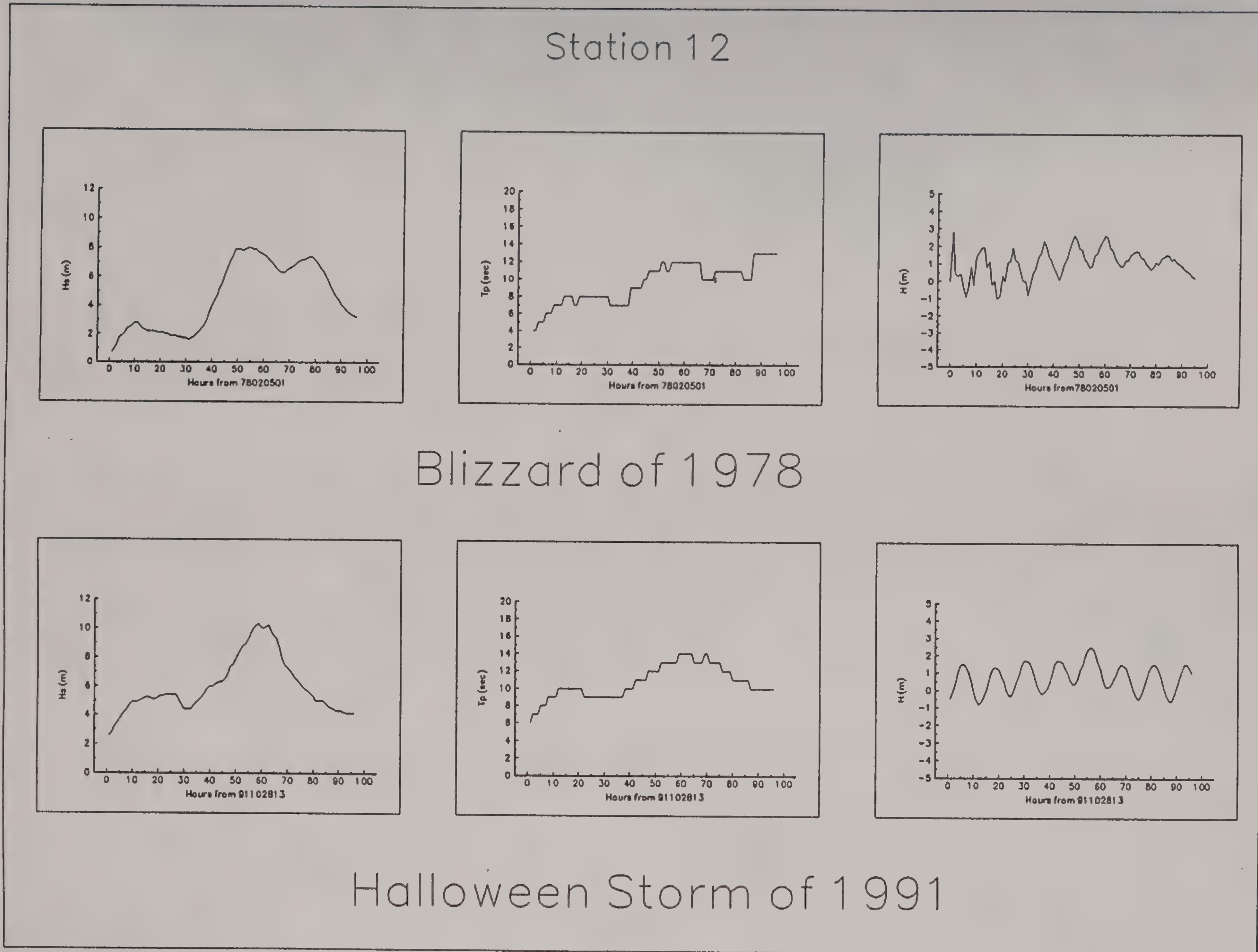

Figure 45. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 12.

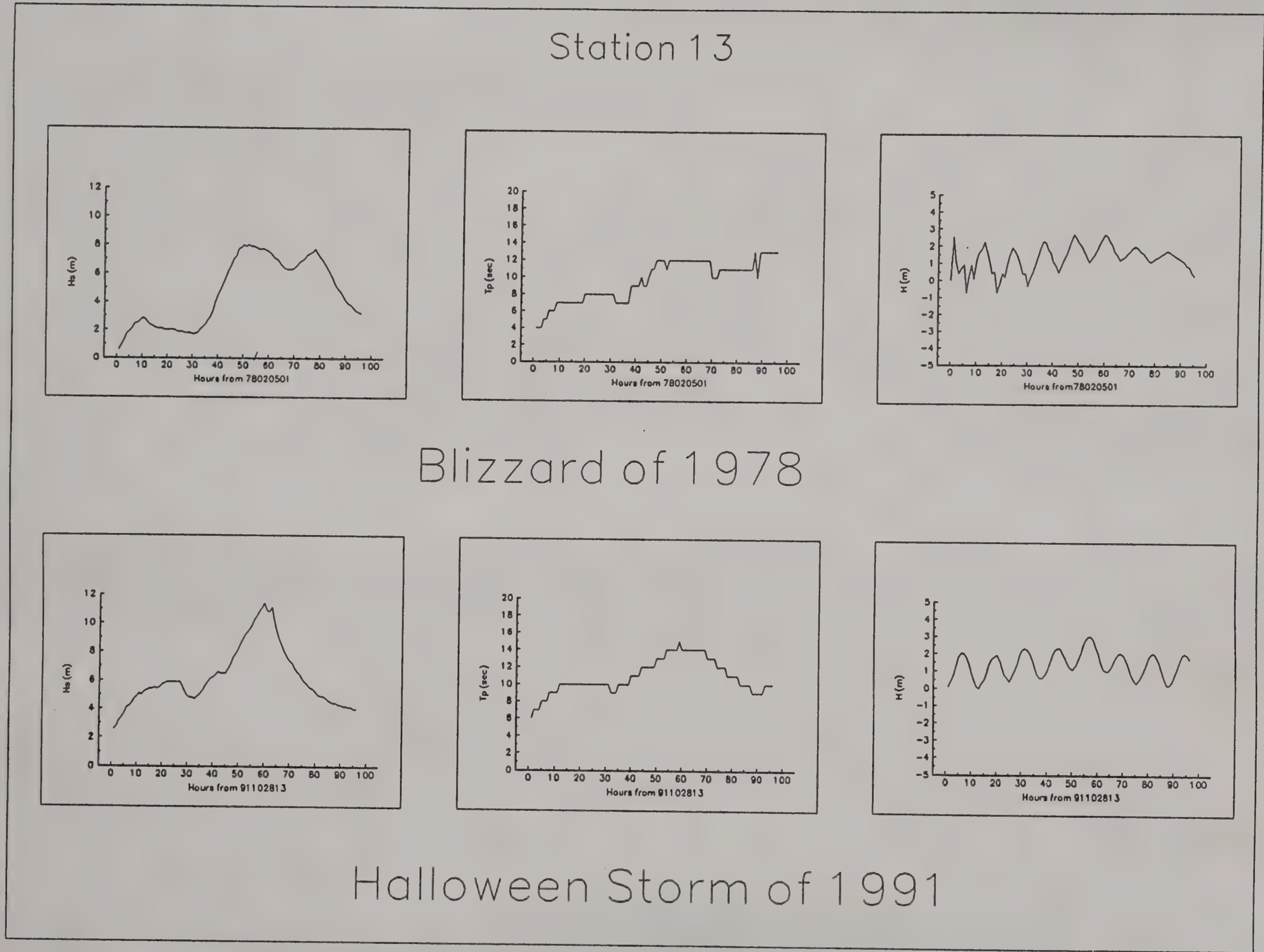

Figure 46. Wave height, peak period, and water level for the Blizzard of 1978 and Halloween storm of 1991 at station 13.

APPENDIX A

SCOPE OF WORK

A Study to Hindcast Wave and Water Level Information for

The Halloween Storm of 1991 & the Blizzard of 1978

It is proposed that the Coastal Engineering Research Center (CERC) hindcast water levels and wave heights for the Halloween Storm of 1991 and the February (Blizzard of 1978) Northeaster. This hindcast will be used by the New England Division (NED) to compare various effects from these two storms on the shoreline from Nantucket to Portland, Maine.

Information from the hindcasts for water level and wave conditions will be provided at points approximately 5 miles apart on a grid incorporating the study area.

The CERC contribution to the NED Study consists of two major tasks;

1. Application of a storm surge hindcast model to provide water levels in the study region for the two storms.

2. Application of a wave hindcast model to provide wave information in the study region for the two storms.

The region for the study is defined as the open coast from Nantucket to Portland, Maine. The water level hindcast will be conducted using the storm surge model SURGE II. This model simulates the non-flooding water level due to the wind induced surge near the coast. Available water level measurements will be used to confirm the model results. The wave hindcast will be conducted using the existing, verified WIS wave model WISWAVE 2.0. Model results will be compared to available measurements to confirm model results. The grids of both models need to cover a large area of the ocean offshore of the region of interest. This is necessary in surge modeling to accurately represent the effects of bathymetry on propagation of the surge nd tide. It is necessary in wave modeling to accurately represent the generation of wave energy by the storm far from shore which subsequently propagates to the shore.

Water Level Hindcast

This portion of the study consists of preparing input files for the model, collecting observed wind, surge, and tidal observations, applying the model for each storm, analyzing the results for accuracy, and preparing the results in the proper format for use in the NED study. Model input files consist of model option parameters for the specific problem, bathymetry over the modeled region, and wind fields and boundary water levels over the region for the duration of each storm. Wind fields and tide levels will be developed and checked for accuracy against available observations.

Wave Hindcast

The numerical grid in the WISWAVE model is composed of latitude, longitude lines. The spacing between grid lines can be varied in a nested grid manner. Thus, a number of grids can be developed of increasing resolution, the finer nested within the coarser. The approach proposed for this study is a 1/2 degree grid over part of the North Atlantic and Georges Bank, and a 5 nautical mile grid nested within, over the region of interest.

This portion of the study consists of preparing input files for the model, collecting observed wind, and wave observations, applying the model for each storm, analyzing the results for accuracy, and preparing the results in the proper format for use in the NED study. Model input files consist of model option parameters for the specific problem, bathymetry over the modeled region, and wind fields and boundary wave information over the region for the duration of each storm. Wind fields will be developed and checked for accuracy against available observations. The surge and wave hindcasts could proceed in parallel assuming availability of personnel.

The output and results shall include, but not be limited to:

1. Water level, wave, and wind histories at specified locations.

2. The history of peak wave height and period with associated direction at specified locations.

3. The maximum, minimum, and mean wave statistics at specified locations.

All input and results will be saved for future use by New England Division personnel. CERC shall provide this data and results for specific areas of interest when requested. The grid and bathymetry files used for the hindcasts will be saved for use in hindcasting future storm events.

Study Report

A brief informal report will be prepared summarizing the study and results. This report will also include a brief description of the modeling process and methodology, and the models limits, capabilities and assumptions.

APPENDIX B

Wave Conditions at Stations 1-13 for Blizzard of 1978

An example of an output record is shown below.

```
001  90102806  024  13  10  165  06  165  00  00  00  003446  0  0  0  0  0  0  1  3  61311  7  5  8101312
6  3  1  0  0  0  0  0  0  046464646  0  0  0  0  0  0  0  0  0
```

The first three digits are the station number. The next eight are the date/time group, which, taken in four groups of two represent the year, month, day, and hour. The example above represents 0600 on October 28, 1990. The next three digits represent the significant wave height in meters times ten. In this example, the value is 2.4 m. The next two values are the peak and mean wave periods to the closest second. In this example, they are 13 and 10 sec, respectively. The next three digits represent the mean wave direction in degrees from which the waves are coming with respect to compass directions. That is, 0 deg is from the north, 90 deg, from the east, etc. In this example, the waves are coming from 165 deg or from a direction between SSE and S. The next two digits are the wind speed in m/sec, 6 m/sec in this case. The next three are the wind direction in degrees in the same convention as the waves. In this example, both the wind and waves are coming from 165 deg. The next two digits represent the water level above a datum. There will be a non-zero value here only if the water level is changed during the simulation as in a hurricane surge or large tidal range case. The value is in meters with respect to the datum chosen; for example, mean sea level or mean low water, or some other datum. The next two digits represent the speed of current flow along a fixed latitude or in the x direction. Values are in meters/second times 10. The next two digits are the similar quantity for flow in the y direction. Positive values are toward the east and north, respectively. The effect of currents on wave propagation and source terms is not accounted for in WISWAVE 2.0, but is planned for the future. The next six digits represent the total energy in the discrete part of the spectrum multiplied by 10,000 and in units of meters squared.

The next 40 spaces contain the percent of total energy density in the discrete part of the spectrum contained in each of the 20 frequency bands for all directions. The center frequencies associated with each of these bands are given in record 4 of the input options file. The hindcast frequency spectrum is obtained using these frequencies, the total discrete energy, and the percentages in each band.

The last 40 spaces contain the mean directions in each frequency band, expressed as a percent of 360 deg. In the example above, in frequency band eight, the 46 represents 46 percent of 360 deg or approximately 165 deg. Thus, in this frequency band, the mean direction from which waves are coming is about 165 deg or from the SSE. The mean across all frequency bands should agree with the mean direction of the spectrum given by the sixth group of numbers in the record. There may be some difference due to rounding off in the averaging process and the resolution of 4 deg imposed by expressing the directions as a percentage of 360 deg.

```
1 78020501   8  6  5  52 17  30  0  0  0    138 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3175020 9 0 0 0 0 0 0 0 0 0 0 0 0 0 0 01515151411
1 78020502  13  4  5  40 16  35  0  0  0    785 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 9281347 0 0 0 0 0 0 0 0 0 0 0 0 0 0 015151513 9
1 78020503  16  5  5  41 15  35  0  0  0   1192 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 9293623 0 0 0 0 0 0 0 0 0 0 0 0 0 0 015151510 9
1 78020504  19  5  5  40 14  35  0  0  0   1882 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 8275211 0 0 0 0 0 0 0 0 0 0 0 0 0 0 01515141010
1 78020505  19  5  5  42 14  40  0  0  0   1926 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 210314710 0 0 0 0 0 0 0 0 0 0 0 0 0 0 01515141010
1 78020506  19  5  5  45 13  40  0  0  0   2024 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2113542 9 0 0 0 0 0 0 0 0 0 0 0 0 0 0 01515151111
1 78020507  19  6  5  48 12  40  0  0  0   2015 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 3133737 9 0 0 0 0 0 0 0 0 0 0 0 0 0 0171616151211
1 78020508  19  6  5  50 12  40  0  0  0   1961 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 5163830 9 0 0 0 0 0 0 0 0 0 0 0 0 0 0181716151211
1 78020509  19  6  5  51 11  40  0  0  0   1930 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 7193924 8 0 0 0 0 0 0 0 0 0 0 0 0 0 0181716151311
1 78020510  19  6  6  53 11  45  0  0  0   1915 0 0 0 0 0 0 0 0 0 0 0 0 0 1 3 9213919 8 0 0 0 0 0 0 0 0 0 0 0 0 018181717151412
1 78020511  19  6  6  55 11  45  0  0  0   1905 0 0 0 0 0 0 0 0 0 0 0 0 0 1 310243915 8 0 0 0 0 0 0 0 0 0 0 0 0 018181817161412
1 78020512  19  6  6  55 10  45  0  0  0   1946 0 0 0 0 0 0 0 0 0 0 0 0 0 1 411253813 8 0 0 0 0 0 0 0 0 0 0 0 0 018181817161412
1 78020513  19  6  6  57 10  50  0  0  0   1947 0 0 0 0 0 0 0 0 0 0 0 0 0 1 513253513 8 0 0 0 0 0 0 0 0 0 0 0 0 018181817161513
1 78020514  19  6  6  59  9  55  0  0  0   1920 0 0 0 0 0 0 0 0 0 0 0 0 0 1 615243213 9 0 0 0 0 0 0 0 0 0 0 0 0 019191817161614
1 78020515  18  6  6  61  9  60  0  0  0   1882 0 0 0 0 0 0 0 0 0 0 0 0 0 2 617232814 9 0 0 0 0 0 0 0 0 0 0 0 0 019191818161716
1 78020516  18  6  6  63  8  65  0  0  0   1826 0 0 0 0 0 0 0 0 0 0 0 0 0 2 71823241510 0 0 0 0 0 0 0 0 0 0 0 0 0 019191918171817
1 78020517  18  7  6  66  7  70  0  0  0   1764 0 0 0 0 0 0 0 0 0 0 0 0 1 3 820222116 9 0 0 0 0 0 0 0 0 0 0 0 01919191918171919
1 78020518  17  8  6  68  7  80  0  0  0   1614 0 0 0 0 0 0 0 0 0 0 0 0 1 31023221817 6 0 0 0 0 0 0 0 0 0 0 01919191918181920
1 78020519  16  8  6  69  6  80  0  0  0   1428 0 0 0 0 0 0 0 0 0 0 0 0 1 31024221718 4 0 0 0 0 0 0 0 0 0 0 01919191918182021
1 78020520  16  8  6  70  5  85  0  0  0   1312 0 0 0 0 0 0 0 0 0 0 0 0 1 31024221718 5 0 0 0 0 0 0 0 0 0 0 01919191919192021
1 78020521  15  8  6  71  5  85  0  0  0   1197 0 0 0 0 0 0 0 0 0 0 0 0 1 31024221718 5 0 0 0 0 0 0 0 0 0 0 01919191919192021
1 78020522  14  8  6  72  4  90  0  0  0   1071 0 0 0 0 0 0 0 0 0 0 0 0 1 31024221717 5 0 0 0 0 0 0 0 0 0 0 01919191919192122
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1 78020612   8  4  5  82  6  70  0  0  0    323 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 918211833 0 0 0 0 0 0 0 0 0 0 0 0 0212121222324
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13	78020701	78	12	9	108	26	70	0	0	0	37805 0 0 0 0 0 0 1 3 61221201412 5 3 1 1 0 0 0 0 0 0 0434241403935322721212020 0
13	78020702	80	12	9	106	25	70	0	0	0	39450 0 0 0 0 0 0 1 3 61220182010 4 2 1 1 0 0 0 0 0 0 0444341403834312321212020 0
13	78020703	79	12	10	102	25	70	0	0	0	38607 0 0 0 0 0 1 1 3 713201919 8 4 2 1 1 0 0 0 0 0 0444341403733292221212020 0
13	78020704	80	11	10	101	24	70	0	0	0	39398 0 0 0 0 0 1 1 3 714202217 7 4 2 1 1 0 0 0 0 0 0474543413936332421212020 20 0
13	78020705	79	12	10	99	23	70	0	0	0	38339 0 0 0 0 0 1 2 4 815201618 8 4 2 1 1 0 0 0 0 0 0484643413935332322212020 20 0
13	78020706	79	12	10	97	23	70	0	0	0	38262 0 0 0 0 0 1 2 4 816201418 9 4 2 1 1 0 0 0 0 0 0494744423935322321212020 20 0
13	78020707	78	12	10	96	22	65	0	0	0	37370 0 0 0 0 0 1 2 4 917211316 9 4 2 1 1 0 0 0 0 0 0504745424035312221202020 20 0
13	78020708	77	12	10	92	22	65	0	0	0	36262 0 0 0 0 0 1 2 4 91721131410 4 2 1 1 0 0 0 0 0 0514845424034302120202019 19 0
13	78020709	77	12	10	86	21	60	0	0	0	36952 0 0 0 0 0 1 2 4 916211317 9 4 2 1 1 0 0 0 0 0 0524845423933281919191918 18 0
13	78020710	77	12	10	82	20	60	0	0	0	36187 0 0 0 0 0 1 2 4 916211417 8 4 2 1 1 0 0 0 0 0 0524945413832241618181817 17 0
13	78020711	76	12	10	78	20	55	0	0	0	35260 0 0 0 0 0 1 2 4 916211317 9 4 2 1 1 0 0 0 0 0 0534945413832221517171717 17 0
13	78020712	75	12	10	75	19	50	0	0	0	34154 0 0 0 0 0 1 2 4 916221316 9 4 2 1 1 0 0 0 0 0 0535045413731231416161616 16 0
13	78020713	73	12	10	73	19	50	0	0	0	32852 0 0 0 0 0 1 2 4 91622131410 4 2 1 1 0 0 0 0 0 0545045403631241215151515 14 0
13	78020714	71	12	10	71	18	50	0	0	0	31383 0 0 0 0 0 1 2 4 91622131311 4 2 1 1 0 0 0 0 0 0545145403530231113141414 14 0
13	78020715	70	12	10	69	18	50	0	0	0	29979 0 0 0 0 0 1 2 4 91522131311 5 2 1 1 0 0 0 0 0 0545145403530231013141414 14 0
13	78020716	68	12	10	67	17	50	0	0	0	28468 0 0 0 0 0 1 2 5 91521131212 5 2 1 1 0 0 0 0 0 053504640353022 91214141414 0
13	78020717	66	12	9	64	17	50	0	0	0	26889 0 0 0 0 1 1 2 5 91520131113 5 2 1 1 0 0 0 0 0 053504640343021 91214141414 0
13	78020718	64	12	9	61	16	50	0	0	0	25311 0 0 0 0 1 1 3 5 91520121014 6 3 1 1 0 0 0 0 0 05352504641342921 81114141414 0
13	78020719	63	12	9	56	17	40	0	0	0	24197 0 0 0 0 1 1 3 5 91419121015 6 3 1 1 0 0 0 0 0 05251504741332922 81014141414 0
13	78020720	63	12	9	49	17	30	0	0	0	24127 0 0 0 0 1 1 3 5 91418111215 6 3 2 1 0 0 0 0 0 05150494641322923 6 913131313 0
13	78020721	63	12	9	41	17	20	0	0	0	24460 0 0 0 0 1 1 3 5 91417101414 6 3 2 1 0 0 0 0 0 04948464339312823 5 911111110 0
13	78020722	64	10	9	33	18	10	0	0	0	25289 0 0 0 0 1 1 3 5 91316111813 5 3 2 1 0 0 0 0 0 047454340362926 20 4 7 9 8 8 8 0
13	78020723	66	10	9	25	18	5	0	0	0	27013 0 0 0 0 1 1 3 5 81315132211 5 3 1 1 0 0 0 0 0 044413936322624 15 4 6 6 6 5 5 0
13	78020800	68	10	9	19	18	355	0	0	0	28098 0 0 0 0 1 1 2 5 81214162110 5 3 1 1 0 0 0 0 0 040373432292421 9 4 5 4 4 3 3 0

13	78020801	69	11	9	16	19	355	0	0	0	29034	0 0 0 0 0 1 1 2 5 812132020 9 4 3 1 1 0 0 0 0 0 032302725231915 5 2 3 2 1 0 0 0
13	78020802	71	11	10	15	19	355	0	0	0	30569	0 0 0 0 0 0 1 2 4 811142418 8 4 2 1 1 0 0 0 0 0 0 0272523211811 4 2 2 1 1 099 0
13	78020803	73	11	10	15	19	350	0	0	0	32874	0 0 0 0 0 0 1 2 4 710172815 7 4 2 1 1 0 0 0 0 0 0 02524222017 8 4 2 2 1 1 099 0
13	78020804	74	11	10	14	19	350	0	0	0	33684	0 0 0 0 0 0 1 2 4 712212613 6 4 2 1 1 0 0 0 0 0 0 02422211914 7 3 1 1 0 09998 0
13	78020805	75	11	10	14	20	350	0	0	0	34998	0 0 0 0 0 0 1 2 4 714232412 6 4 2 1 1 0 0 0 0 0 0 02221201814 7 3 1 1 0 09998 0
13	78020806	77	11	10	15	20	350	0	0	0	36109	0 0 0 0 0 0 1 2 3 714242411 6 4 2 1 1 0 0 0 0 0 0 02121201815 8 3 1 1 0 09998 0
13	78020807	74	11	10	15	19	350	0	0	0	33935	0 0 0 0 0 0 1 2 4 714232412 6 4 2 1 1 0 0 0 0 0 0 02120191815 8 3 1 1 0 09998 0
13	78020808	71	11	10	15	19	350	0	0	0	31289	0 0 0 0 0 0 1 2 4 712212413 7 4 2 1 1 0 0 0 0 0 0 02120201816 8 3 1 1 0 09998 0
13	78020809	69	11	10	14	18	350	0	0	0	28812	0 0 0 0 0 0 1 2 4 711192514 7 4 3 1 1 0 0 0 0 0 0 02121201917 9 3 1 1 0 09998 0
13	78020810	66	11	9	16	18	355	0	0	0	26673	0 0 0 0 0 0 1 2 4 710172515 8 5 3 1 1 0 0 0 0 0 0 0212120191710 3 1 1 1 0 099 0
13	78020811	63	11	9	17	17	355	0	0	0	24366	0 0 0 0 0 0 1 2 5 811152415 8 5 3 2 1 0 0 0 0 0 0 0212120201811 4 1 1 1 1 099 0
13	78020812	60	11	9	18	17	355	0	0	0	21906	0 0 0 0 0 1 1 3 5 811132116 9 5 3 2 1 0 0 0 0 0 020212121201913 5 1 1 1 1 099 0
13	78020813	56	11	9	20	16	355	0	0	0	18852	0 0 0 0 0 1 1 3 6 91213181510 6 4 2 1 0 0 0 0 0 020212121202014 5 1 1 1 1 099 0
13	78020814	52	11	9	21	15	355	0	0	0	16483	0 0 0 0 0 1 2 3 6101313151310 6 4 2 1 0 0 0 0 0 020212121212015 6 2 1 1 1 0 0 0
13	78020815	49	13	9	24	14	355	0	0	0	14780	0 0 0 0 0 1 2 3 71114131314 9 6 4 2 1 0 0 0 0 0 020212121212117 6 2 1 1 1 0 0 0
13	78020816	47	10	9	26	13	0	0	0	0	13372	0 0 0 0 0 1 2 4 71214131115 9 6 4 2 1 0 0 0 0 0 020202121212218 8 3 1 1 1 1 0 0
13	78020817	44	13	9	30	12	0	0	0	0	11662	0 0 0 0 0 1 2 4 81315131013 8 6 4 2 1 0 0 0 0 0 020202121212219 8 4 2 1 1 1 1 0
13	78020818	41	13	9	32	11	0	0	0	0	10335	0 0 0 0 0 1 2 4 8141613 911 9 5 3 2 1 0 0 0 0 0 020202121212219 8 4 2 2 1 1 1 0
13	78020819	39	13	9	33	10	0	0	0	0	9463	0 0 0 0 0 1 2 4 9151713 81011 5 3 2 1 0 0 0 0 0 020202121212220 8 5 2 2 2 1 1 0
13	78020820	38	13	9	35	9	355	0	0	0	8625	0 0 0 0 0 1 2 4 9151812 7 911 5 3 2 1 0 0 0 0 0 020202121212220 9 5 2 2 2 1 0 0
13	78020821	36	13	9	37	8	355	0	0	0	7840	0 0 0 0 0 1 2 4 9161912 7 811 5 3 2 1 0 0 0 0 0 019202121212220 9 6 3 2 2 1 0 0
13	78020822	34	13	9	39	8	350	0	0	0	7128	0 0 0 0 0 1 2 4 9172112 6 7 9 6 3 2 1 0 0 0 0 0 01920202121222010 6 3 2 2 199 0
13	78020823	33	13	9	41	7	345	0	0	0	6536	0 0 0 0 0 1 2 4 9182212 6 6 8 6 3 2 1 0 0 0 0 0 01920202121222011 7 4 2 2 299 0
13	78020900	32	13	9	43	6	340	0	0	0	6040	0 0 0 0 0 1 1 4 9192312 6 6 7 6 3 1 1 0 0 0 0 0 01919202121222011 7 5 2 3 2 0 0

APPENDIX C

Wave Conditions at Stations 1-13 for Halloween Storm of 1991

n example of an output record is shown below.

```
001  90102806  024  13  10  165  06  165  00  00  00  003446  0  0  0  0  0  0  1  3  61311  7  5  8101312  6  3  1  0  0  0  0  0
  046464646  0  0  0  0  0  0  0  0  0
```

The first three digits are the station number. The next eight are the date/time group, which, taken in four groups of two represent the year, month, day, and hour. The example above represents 0600 on October 28, 1990. The next three digits represent the significant wave height in meters times ten. In this example, the value is 2.4 m. The next two values are the peak and mean wave periods to the closest second. In this example, they are 13 and 10 sec, respectively. The next three digits represent the mean wave direction in degrees from which the waves are coming with respect to compass directions. That is, 0 deg is from the north, 90 deg, from the east, etc. In this example, the waves are coming from 165 deg or from a direction between SSE and S. The next two digits are the wind speed in m/sec, 6 m/sec in this case. The next three are the wind direction in degrees in the same convention as the waves. In this example, both the wind and waves are coming from 165 deg. The next two digits represent the water level above a datum. There will be a non-zero value here only if the water level is changed during the simulation as in a hurricane surge or large tidal range case. The value is in meters with respect to the datum chosen; for example, mean sea level or mean low water, or some other datum. The next two digits represent the speed of current flow along a fixed latitude or in the x direction. Values are in meters/second times 10. The next two digits are the similar quantity for flow in the y direction. Positive values are toward the east and north, respectively. The effect of currents on wave propagation and source terms is not accounted for in WISWAVE 2.0, but is planned for the future. The next six digits represent the total energy in the discrete part of the spectrum multiplied by 10,000 and in units of meters squared.

The next 40 spaces contain the percent of total energy density in the discrete part of the spectrum contained in each of the 20 frequency bands for all directions. The center frequencies associated with each of these bands are given in record 4 of the input options file. The hindcast frequency spectrum is obtained using these frequencies, the total discrete energy, and the percentages in each band.

The last 40 spaces contain the mean directions in each frequency band, expressed as a percent of 360 deg. In the example above, in frequency band eight, the 46 represents 46 percent of 360 deg or approximately 165 deg. Thus, in this frequency band, the mean direction from which waves are coming is about 165 deg or from the SSE. The mean across all frequency bands should agree with the mean direction of the spectrum given by the sixth group of numbers in the record. There may be some difference due to rounding off in the averaging process and the resolution of 4 deg imposed by expressing the directions as a percentage of 360 deg.

1	91102813	17	7	5	18	16	350	0	0	0	1361 0 0 0 0 0 0 0 0 0 0 1 1 2 2 31024162019 0 0 0 0 0 0 0 0 041403837353020 9 197
1	91102814	16	7	5	16	16	350	0	0	0	1278 0 0 0 0 0 0 0 0 0 0 1 1 2 4 61122131920 0 0 0 0 0 0 0 0 041403837363119 8 097
1	91102815	16	4	5	16	16	355	0	0	0	1230 0 0 0 0 0 0 0 0 0 1 1 2 3 6 81118111921 0 0 0 0 0 0 0 04241403937363218 7 098
1	91102816	16	4	5	18	15	355	0	0	0	1213 0 0 0 0 0 0 0 0 0 1 1 2 4 8101015121721 0 0 0 0 0 0 0 04241403937363217 7 199
1	91102817	16	4	5	19	15	355	0	0	0	1206 0 0 0 0 0 0 0 0 0 1 1 2 4 911 913121621 0 0 0 0 0 0 0 04241403937363215 7 199
1	91102818	16	4	5	20	15	0	0	0	0	1201 0 0 0 0 0 0 0 0 0 1 1 2 51011 912131620 0 0 0 0 0 0 0 04241403937353113 8 199
1	91102819	16	4	5	24	15	5	0	0	0	1182 0 0 0 0 0 0 0 0 0 1 2 3 61112 810141321 0 0 0 0 0 0 0 04241403937353012 8 2 1
1	91102820	16	4	5	30	14	10	0	0	0	1185 0 0 0 0 0 0 0 0 0 1 2 4 71112 8 9161120 0 0 0 0 0 0 0 04342413937352911 9 5 2
1	91102821	16	4	5	38	14	20	0	0	0	1189 0 0 0 0 0 0 0 0 0 1 2 5 91112 7 716 920 0 0 0 0 0 0 0 04342413937352711 9 7 4
1	91102822	16	4	5	40	14	10	0	0	0	1283 0 0 0 0 0 0 0 0 0 1 2 6101212 6 717 918 0 0 0 0 0 0 0 043424139373425111 0 8 4
1	91102823	17	6	5	39	14	5	0	0	0	1393 0 0 0 0 0 0 0 0 0 1 2 6111212 6 719 816 0 0 0 0 0 0 0 043424139373423111 0 7 2
1	91102900	17	6	6	37	15	0	0	0	0	1506 0 0 0 0 0 0 0 0 0 1 2 7121312 5 819 814 0 0 0 0 0 0 0 04342414038342111 10 6 1
1	91102901	17	6	6	38	15	0	0	0	0	1566 0 0 0 0 0 0 0 0 0 1 3 8131512 4 816 812 0 0 0 0 0 0 0 04342414038341911 10 4 0
1	91102902	18	10	6	39	15	0	0	0	0	1604 0 0 0 0 0 0 0 0 1 4 9151612 4 712 811 0 0 0 0 0 0 0 043434240383418 11 9 4 0
1	91102903	18	10	6	42	15	0	0	0	0	1654 0 0 0 0 0 0 0 0 2 511161711 4 710 810 0 0 0 0 0 0 0 043434241393317 11 8 3 0
1	91102904	18	10	6	48	15	0	0	0	0	1679 0 0 0 0 0 0 0 1 2 612181810 4 6 8 6 9 0 0 0 0 0 0 0434343424139321611 8 3 0
1	91102905	18	11	6	56	15	5	0	0	0	1719 0 0 0 0 0 0 0 1 3 8141918 8 4 4 7 5 9 0 0 0 0 0 0 0434343424139311611 8 4 1
1	91102906	18	11	6	66	14	5	0	0	0	1757 0 0 0 0 0 0 0 1 4 9162118 7 4 3 6 3 8 0 0 0 0 0 0 0434343434139291610 9 5 1
1	91102907	18	11	6	75	14	10	0	0	0	1818 0 0 0 0 0 0 0 0 2 510172216 6 3 3 6 3 7 0 0 0 0 0 0 0434343434239271510 9 6 2
1	91102908	19	11	7	80	14	10	0	0	0	1911 0 0 0 0 0 0 0 1 2 612192214 5 3 2 5 3 7 0 0 0 0 0 0 043434343434239251511 9 7 3
1	91102909	19	11	7	85	13	15	0	0	0	2000 0 0 0 0 0 0 0 1 3 713202211 4 3 2 5 3 6 0 0 0 0 0 0 043434343434239231511 10 8 4
1	91102910	20	11	7	88	13	10	0	0	0	2081 0 0 0 0 0 0 1 2 4 8142122 9 3 3 2 5 2 5 0 0 0 0 0 04343434343434239221511 10 8 4
1	91102911	20	12	7	91	13	10	0	0	0	2162 0 0 0 0 0 0 1 2 5 9152120 7 3 3 2 5 2 5 0 0 0 0 0 04343434343434239201511 10 8 3
1	91102912	20	12	7	93	14	5	0	0	0	2230 0 0 0 0 0 0 1 3 611162118 5 2 2 2 5 2 5 0 0 0 0 0 043434343434342381915111 1 7 2
1	91102913	20	12	7	97	13	5	0	0	0	2271 0 0 0 0 0 1 2 4 712172116 4 2 2 2 4 2 4 0 0 0 0 044434343434343423718151211 7 2
1	91102914	20	12	7	101	13	5	0	0	0	2288 0 0 0 0 0 1 2 5 913182013 3 2 2 1 4 2 4 0 0 0 0 044434343434343423517151211 7 2
1	91102915	20	12	7	103	13	5	0	0	0	2282 0 0 0 0 0 1 3 61015191911 2 2 3 1 3 1 4 0 0 0 0 043434343434343423317151211 7 2
1	91102916	19	13	8	107	12	5	0	0	0	2199 0 0 0 0 0 1 3 711161918 9 2 2 3 1 3 1 4 0 0 0 0 043434343434343412917151210 8 2
1	91102917	19	13	8	112	12	15	0	0	0	1997 0 0 0 0 0 1 4 712172017 7 2 2 3 1 2 1 3 0 0 0 0 043434343434343412617151210 9 3
1	91102918	18	13	8	114	11	20	0	0	0	1783 0 0 0 0 0 1 4 813182016 6 2 2 3 1 2 2 2 0 0 0 0 043434343434343402417151211 9 5
1	91102919	17	13	8	107	11	10	0	0	0	1692 0 0 0 0 0 1 4 813192015 5 2 2 3 1 2 2 3 0 0 0 0 0434343434343433922171512111 0 4
1	91102920	17	13	7	96	12	5	0	0	0	1614 0 0 0 0 0 1 4 814192013 5 2 2 3 1 2 3 4 0 0 0 0 0434343434343423621171512111 0 2
1	91102921	16	14	7	84	12	0	0	0	0	1516 0 0 0 0 0 1 4 813191912 4 3 2 3 1 3 2 5 0 0 0 0 043434343434342332017151311 9 1
1	91102922	16	14	7	70	12	10	0	0	0	1471 0 0 0 0 0 1 3 813191811 5 3 3 3 1 4 2 6 0 0 0 0 043434343434241302017151311 9 2
1	91102923	17	14	6	61	13	20	0	0	0	1499 0 0 0 0 0 1 3 712181610 5 4 3 3 2 5 3 7 0 0 0 0 043434343424138272017151311 9 5
1	91103000	17	14	6	59	13	30	0	0	0	1537 0 0 0 0 0 1 3 7111715 9 5 4 3 3 3 7 5 7 0 0 0 0 0424242424140352621171513111 0 7
1	91103001	20	14	6	55	13	30	0	0	0	2126 0 0 0 0 0 1 3 6 91412 8 4 4 3 3 51212 5 0 0 0 0 042424141403732252117161413 11 9
1	91103002	23	6	6	52	14	30	0	0	0	2978 0 0 0 0 0 1 2 5 711 9 7 4 3 2 4101616 3 0 0 0 0 040404040393529242118161514 10 9
1	91103003	25	6	6	54	14	30	0	0	0	3413 0 0 0 0 0 1 2 4 7 9 7 6 3 3 2 6151614 3 0 0 0 0 0383838383732272421181716151010
1	91103004	26	7	6	54	14	25	0	0	0	3729 0 0 0 0 1 1 3 4 6 8 7 5 3 3 3 7181512 3 0 0 0 0333436363635302523211917171 5 9 9
1	91103005	27	7	6	55	14	25	0	0	0	4049 0 0 0 0 1 2 3 5 7 8 6 5 3 4 5 8181310 2 0 0 0 0303132333333282523212018171 5 9 8
1	91103006	28	7	7	57	14	25	0	0	0	4459 0 0 0 0 1 2 3 5 7 8 5 4 3 6 8 91611 9 2 0 0 0 0282930313131272423222019171 5 9 8
1	91103007	29	7	7	58	15	20	0	0	0	5065 0 0 0 0 1 2 3 5 7 8 5 4 4 7101014 9 8 2 0 0 0 026272829292926242322201917 14 8 7
1	91103008	31	7	7	59	15	20	0	0	0	5733 0 0 0 1 1 2 4 5 7 8 4 4 5 8111212 7 7 1 0 0 025262627272727252423222119171 4 7 7
1	91103009	33	9	7	61	15	20	0	0	0	6384 0 0 0 1 1 2 4 6 8 7 4 4 6 9121111 6 6 1 0 0 025252626262626252423222119171 4 7 7
1	91103010	34	9	7	62	15	20	0	0	0	7019 0 0 0 1 2 3 4 6 8 7 4 5 8101210 9 5 5 1 0 0 025252525262626252423222119171 4 7 7
1	91103011	36	9	8	65	15	25	0	0	0	7662 0 0 0 1 2 3 5 7 8 7 3 6 91111 8 8 4 4 1 0 0 025252525252525252423222118171 4 8 8
1	91103012	37	10	8	67	15	30	0	0	0	8250 0 0 0 1 3 4 6 8 9 6 4 6101110 7 7 4 3 1 0 0 025252525252525252423222018171 4 9 9
1	91103013	39	10	8	68	16	25	0	0	0	9170 0 0 0 2 3 5 7 910 6 4 71010 9 6 7 4 2 1 0 0 025252525252525252423222018171 4 9 9
1	91103014	41	15	8	69	16	20	0	0	0	10331 0 0 0 2 3 5 71010 6 4 710 9 8 5 7 4 2 1 0 0 025252525252525252423222018171 3 8 7
1	91103015	43	15	8	69	17	20	0	0	0	11330 0 0 0 2 3 5 81011 6 5 810 9 8 4 6 2 2 1 0 0 025252525252525252423222018161 3 7 7
1	91103016	45	15	9	71	17	20	0	0	0	12339 0 0 0 1 3 5 81112 5 6 911 8 7 4 5 2 2 0 0 0 026252525252525252423222018151 3 7 0
1	91103017	48	15	9	73	17	25	0	0	0	14035 0 0 0 1 3 5 81112 5 61011 7 7 3 5 3 1 0 0 0 026262525252525252423222018151 3 9 0
1	91103018	50	15	9	74	17	20	0	0	0	15415 0 0 0 1 3 5 81112 5 71111 7 7 3 4 2 1 0 0 0 026262625252525252423222018151 3 9 0
1	91103019	52	15	9	75	17	20	0	0	0	16670 0 0 0 1 3 5 81113 5 81211 6 7 3 4 2 1 0 0 0 027262625252526252423212018151 3 9 0
1	91103020	54	15	9	75	18	25	0	0	0	18004 0 0 0 2 3 5 81113 6 81211 6 6 3 4 3 1 0 0 0 027262626252526252423212018151 2 9 0
1	91103021	56	15	9	75	18	25	0	0	0	19126 0 0 0 1 3 5 81113 6 81211 6 6 3 3 3 1 0 0 0 027262626252526252423212017151 2 9 0
1	91103022	57	15	9	75	18	25	0	0	0	19887 0 0 0 1 3 5 81114 6 81211 6 6 3 3 3 1 0 0 0 027262626252526252423212017151 2 8 0
1	91103023	58	15	9	76	18	30	0	0	0	20735 0 0 0 1 3 5 81114 6 81211 6 6 3 3 2 1 0 0 0 027262626252526252423212018161 2 9 0
1	91103100	60	15	10	77	18	30	0	0	0	21725 0 0 0 1 2 4 71114 7 81211 6 6 3 3 3 1 0 0 0 027262626262526252524222018161 2 9 0
1	91103101	60	15	10	77	18	30	0	0	0	22242 0 0 0 1 2 4 71114 7 81312 6 6 3 3 2 1 0 0 0 027272626262626252422201815 11 9 0
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13	91103100	114	14	12	41	24	5	0	0	0	80580 0 0 0 1 2 4 813192013 7 5 3 2 1 1 0 0 0 0 0 021202019181712 9 7 6 6 5 4 3 0 0 0
13	91103101	109	14	12	40	23	10	0	0	0	74201 0 0 0 1 2 4 712182113 8 5 3 2 1 1 0 0 0 0 0 021202019191713 9 7 6 6 5 4 4 0 0 0
13	91103102	108	14	12	41	23	15	0	0	0	71866 0 0 0 1 2 4 812181913 8 5 4 2 1 1 0 0 0 0 0 021202019191713 9 8 7 6 5 5 4 0 0 0
13	91103103	111	14	12	42	23	20	0	0	0	75705 0 0 0 1 2 4 813191912 7 5 3 2 1 1 0 0 0 0 0 021202019181712 9 8 7 7 6 6 6 0 0 0
13	91103104	102	14	11	41	22	30	0	0	0	64287 0 0 0 1 2 4 711172014 9 6 4 3 2 1 1 0 0 0 0 0201919191818171210 9 8 8 7 7 7 7 0 0
13	91103105	95	14	11	44	21	35	0	0	0	55847 0 0 0 1 2 3 61014201510 7 5 3 2 1 1 0 0 0 0 0202019191817141110 9 9 9 9 9 9 0 0
13	91103106	89	14	11	48	20	45	0	0	0	49360 0 0 0 1 1 3 61114181511 8 5 3 2 1 1 0 0 0 0 020201919191715121111111111111 0 0
13	91103107	84	14	11	50	19	40	0	0	0	43777 0 0 0 0 1 3 61115181311 8 6 4 2 1 1 0 0 0 0 0 0202020191816131212121212121212 0 0
13	91103108	80	14	11	51	18	35	0	0	0	39501 0 0 0 0 1 2 51015181410 8 6 4 2 1 1 0 0 0 0 0 0202020201917141212121212121111 0 0
13	91103109	76	14	11	52	17	30	0	0	0	35683 0 0 0 0 1 2 4 915181711 8 6 4 3 1 1 0 0 0 0 0 0202020202018161312111111111110 0 0
13	91103110	74	13	11	54	16	35	0	0	0	33565 0 0 0 0 0 1 3 814181813 8 6 4 3 2 1 0 0 0 0 0 0 020212120201715121111111010 0 0
13	91103111	72	13	10	55	16	35	0	0	0	31552 0 0 0 0 0 1 3 712171915 9 7 5 3 2 1 0 0 0 0 0 0 020202121201916131111111010 0 0
13	91103112	69	13	10	56	16	40	0	0	0	29662 0 0 0 0 0 1 2 51116181710 7 5 3 2 1 1 0 0 0 0 0 0 020202121211917141212111111111 0

13	91103113	66	13	10	56	16	40	0	0	0	27119	0 0 0 0 0 0 2 41016181810 8 6 4 2 1 1 0 0 0 0 0 0 02020212120181412121111111 0
13	91103114	64	12	10	57	15	40	0	0	0	24936	0 0 0 0 0 0 1 4 915181912 8 6 4 2 1 1 0 0 0 0 0 0 02020202121191513121111111 0
13	91103115	61	12	10	57	15	40	0	0	0	23166	0 0 0 0 0 0 1 3 714181915 8 6 4 2 1 1 0 0 0 0 0 0 01920202121191613121111111 0
13	91103116	59	12	10	58	14	40	0	0	0	21344	0 0 0 0 0 0 1 2 713171917 8 6 4 3 1 1 0 0 0 0 0 0 01920202121201713121111111 0
13	91103117	57	12	10	59	13	40	0	0	0	20038	0 0 0 0 0 0 1 2 61217191811 6 4 3 1 1 0 0 0 0 0 0 01920202121211815121111111 0
13	91103118	55	11	10	60	13	40	0	0	0	18786	0 0 0 0 0 0 0 2 51116191913 6 4 3 1 1 0 0 0 0 0 0 0 020202121211916121111111 0
13	91103119	54	11	9	60	13	40	0	0	0	18006	0 0 0 0 0 0 0 1 41015181915 7 5 3 2 1 0 0 0 0 0 0 0 020202121222017131111111 0
13	91103120	52	11	9	61	13	35	0	0	0	16792	0 0 0 0 0 0 0 1 3 915181916 7 5 3 2 1 0 0 0 0 0 0 0 019202021222018131111111 0
13	91103121	50	11	9	62	11	35	0	0	0	15575	0 0 0 0 0 0 0 1 3 814181918 9 4 3 2 1 0 0 0 0 0 0 0 019202021222118161111010 0
13	91103122	49	11	9	63	12	30	0	0	0	14922	0 0 0 0 0 0 0 1 2 71417191811 5 3 2 1 0 0 0 0 0 0 0 0192020212222191711101 0 9 0
13	91103123	49	10	9	62	12	30	0	0	0	14458	0 0 0 0 0 0 0 0 2 61317181813 6 4 2 1 0 0 0 0 0 0 0 0 0202021222320171110 9 9 0
13	91110100	48	10	9	61	12	30	0	0	0	14005	0 0 0 0 0 0 0 0 2 61216171815 7 4 2 1 0 0 0 0 0 0 0 0 02020212223211710 9 9 9 0
13	91110101	46	10	9	60	12	35	0	0	0	13107	0 0 0 0 0 0 0 0 1 51216171816 6 4 2 1 0 0 0 0 0 0 0 0 0202021222321171010 9 9 0
13	91110102	45	10	9	60	12	35	0	0	0	12474	0 0 0 0 0 0 0 0 1 41115171817 7 5 3 1 0 0 0 0 0 0 0 0 02020212223201610101010 0
13	91110103	44	10	9	59	12	35	0	0	0	11907	0 0 0 0 0 0 0 0 1 41015171818 7 5 3 1 1 0 0 0 0 0 0 0 0202021222220161010101010
13	91110104	44	9	8	57	12	35	0	0	0	11508	0 0 0 0 0 0 0 0 1 3 915171919 7 5 3 1 1 0 0 0 0 0 0 0 0202021222220161010101010
13	91110105	43	9	8	56	12	35	0	0	0	11213	0 0 0 0 0 0 0 0 1 3 914171920 8 5 3 1 1 0 0 0 0 0 0 0 0202021212219161010101010
13	91110106	43	9	8	54	12	30	0	0	0	11022	0 0 0 0 0 0 0 0 0 2 814171920 8 6 3 2 1 0 0 0 0 0 0 0 0 02021212119151010 9 9 9
13	91110107	42	9	8	52	12	30	0	0	0	10892	0 0 0 0 0 0 0 0 0 2 713171921 9 6 3 2 1 0 0 0 0 0 0 0 0 02020212118151 0 9 9 9 9
13	91110108	42	9	8	51	13	30	0	0	0	10831	0 0 0 0 0 0 0 0 0 1 61217202110 6 4 2 1 0 0 0 0 0 0 0 0 0 02020212018151 0 9 9 9 8
13	91110109	41	10	8	49	13	30	0	0	0	10012	0 0 0 0 0 0 0 0 0 1 61318211611 7 4 2 1 0 0 0 0 0 0 0 0 0 02020202017141 0 9 9 9 8
13	91110110	41	10	8	48	13	35	0	0	0	9939	0 0 0 0 0 0 0 0 0 1 51218211712 8 4 2 1 0 0 0 0 0 0 0 0 0 02020201917131 0 9 9 9 9
13	91110111	40	10	8	47	13	35	0	0	0	9716	0 0 0 0 0 0 0 0 0 1 41117221712 8 4 2 1 0 0 0 0 0 0 0 0 0 0202020191613101010101 0
13	91110112	40	10	8	48	13	40	0	0	0	9445	0 0 0 0 0 0 0 0 0 1 41118221712 8 4 2 1 0 0 0 0 0 0 0 0 0 0191919181613111010101 0
13	91110113	39	10	8	48	13	35	0	0	0	9303	0 0 0 0 0 0 0 0 0 1 31017221912 8 4 2 1 0 0 0 0 0 0 0 0 0 0181919181614111010101 0
13	91110114	39	10	8	47	12	30	0	0	0	9109	0 0 0 0 0 0 0 0 0 0 31017232111 8 4 2 1 0 0 0 0 0 0 0 0 0 0 01919181614101010 9 9
13	91110115	38	9	8	47	12	30	0	0	0	8851	0 0 0 0 0 0 0 0 0 0 2 917232311 7 4 2 1 0 0 0 0 0 0 0 0 0 0 0191918161510 1 0 9 9 9
13	91110116	38	9	8	47	11	25	0	0	0	8480	0 0 0 0 0 0 0 0 0 0 2 817232511 7 4 2 1 0 0 0 0 0 0 0 0 0 0 0181918161510 9 9 8 8
13	91110117	37	9	8	47	10	25	0	0	0	8063	0 0 0 0 0 0 0 0 0 0 2 816232711 6 4 2 1 0 0 0 0 0 0 0 0 0 0 0181919171510 8 8 8 7
13	91110118	36	9	8	49	9	20	0	0	0	7647	0 0 0 0 0 0 0 0 0 0 1 716232813 6 3 2 1 0 0 0 0 0 0 0 0 0 0 0191919171611 8 8 7 7

APPENDIX D

Water Level at Stations 1-13 for Blizzard of 1978

Station	1	2	3	4	5	6	7	8	9	10	11	12	13
Time Hours from 78020501 UTC / Water Level (m) NGVD													
1.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	2.5
2.0	0.8	1.8	2.4	0.3	1.4	1.4	1.0	0.1	0.2	0.6	0.2	0.4	1.1
3.0	0.2	0.7	0.5	2.1	2.5	2.2	1.5	2.3	2.2	1.4	1.3	0.3	0.4
4.0	-0.3	0.5	-0.1	0.2	-0.2	0.1	0.4	1.0	0.8	1.2	1.8	0.4	0.7
5.0	-1.0	-0.7	-1.3	-0.8	-0.3	0.0	0.3	0.7	0.6	0.3	0.8	-0.4	0.9
6.0	-1.5	-1.4	-0.4	-0.6	-1.0	-1.2	-1.4	-1.6	-1.6	-1.4	-1.2	-0.9	-0.7
7.0	-1.3	-2.3	-2.1	-2.5	-2.3	-2.5	-2.8	-2.6	-2.7	-3.1	-3.5	-0.4	0.2
8.0	-0.7	-0.7	-1.4	-2.7	-2.7	-2.9	-3.0	-2.6	-2.7	-3.0	-4.2	0.8	0.9
9.0	-0.7	-1.4	-1.1	-1.3	-1.4	-1.7	-2.4	-2.7	-2.8	-2.8	-2.7	-0.2	0.1
10.0	0.4	0.7	0.4	-0.6	0.0	-0.1	-0.1	-0.5	-0.3	-0.4	-0.7	1.4	1.2
11.0	1.5	1.5	1.0	1.9	1.8	1.9	2.1	2.3	2.2	1.9	1.9	1.6	1.6
12.0	2.1	2.8	3.0	3.3	2.9	3.0	3.1	3.1	3.3	3.1	3.8	1.9	1.8
13.0	2.9	2.9	2.8	3.4	3.9	4.1	4.1	4.1	4.1	4.2	4.3	1.9	2.2
14.0	1.4	1.8	2.5	3.0	3.3	3.5	3.6	3.6	3.7	3.7	3.8	0.8	1.7
15.0	0.4	0.1	0.7	1.0	1.1	1.1	0.9	0.5	0.7	1.2	2.1	1.1	1.1
16.0	-0.7	-0.9	-1.2	-1.8	-1.3	-1.1	-0.8	-0.7	-0.7	-0.6	-0.9	-0.2	0.4
17.0	-1.7	-1.7	-2.0	-1.9	-2.2	-2.3	-2.6	-3.1	-3.0	-2.8	-3.3	0.0	0.5
18.0	-2.6	-2.5	-2.1	-3.0	-3.0	-3.1	-3.5	-3.8	-3.7	-3.7	-4.2	-1.0	-0.7
19.0	-2.0	-2.1	-3.1	-3.2	-3.3	-3.2	-3.2	-3.1	-3.1	-3.1	-4.2	-0.9	-0.2
20.0	-1.6	-1.7	-2.3	-2.8	-2.9	-3.0	-2.9	-2.6	-2.7	-2.8	-2.5	0.3	0.4
21.0	-0.5	-0.7	-0.6	-0.5	-0.8	-1.0	-1.1	-1.1	-1.3	-1.3	-0.9	0.0	0.2
22.0	0.9	1.0	1.4	1.1	1.2	1.2	1.2	1.8	1.6	1.1	0.4	1.1	1.0
23.0	1.5	1.3	2.0	2.2	2.1	2.0	1.9	1.9	1.9	2.0	2.4	1.1	1.5
24.0	2.1	2.2	2.2	2.5	2.5	2.6	2.9	3.4	3.2	3.0	3.6	1.9	1.9
25.0	2.0	2.1	2.1	2.3	2.6	2.6	2.8	2.9	2.9	3.0	3.3	1.2	1.7
26.0	0.9	1.0	2.0	2.1	2.0	2.0	1.9	1.9	2.0	2.1	2.0	1.1	1.4
27.0	0.4	0.5	0.3	0.4	0.5	0.7	0.6	0.4	0.4	0.6	0.5	0.6	1.0
28.0	-0.8	-0.9	-1.1	-1.4	-1.3	-1.2	-1.1	-1.2	-1.1	-1.1	-1.0	0.0	0.4
29.0	-1.6	-1.7	-1.9	-1.7	-1.8	-1.8	-2.1	-2.3	-2.2	-2.3	-2.2	0.0	0.4
30.0	-1.9	-2.0	-2.2	-2.4	-2.2	-2.2	-2.3	-2.6	-2.5	-2.4	-3.1	-0.8	-0.3
31.0	-1.8	-1.9	-2.2	-2.3	-2.3	-2.4	-2.4	-2.6	-2.5	-2.5	-2.8	-0.1	0.2
32.0	-1.0	-1.0	-1.7	-2.0	-2.1	-2.1	-2.1	-2.1	-2.2	-2.2	-1.9	0.5	0.5
33.0	0.1	-0.1	-0.2	-0.2	-0.5	-0.6	-0.5	-0.4	-0.5	-0.6	-0.9	0.7	0.9
34.0	1.0	1.2	1.5	1.3	1.4	1.3	1.1	1.1	1.1	0.9	0.7	1.4	1.4
35.0	1.8	1.7	2.1	2.3	2.2	2.2	2.3	2.4	2.3	2.3	2.6	1.6	1.9
36.0	2.6	2.6	2.8	2.7	2.8	2.9	3.2	3.6	3.4	3.3	3.8	2.3	2.3
37.0	2.6	2.6	2.9	3.2	3.2	3.2	3.3	3.4	3.4	3.4	3.7	2.0	2.2
38.0	1.8	1.9	2.8	3.3	2.9	2.9	3.0	3.2	3.1	3.2	2.9	1.4	1.8
39.0	0.9	0.9	1.1	0.8	1.3	1.4	1.4	1.3	1.3	1.3	1.7	1.2	1.6
40.0	-0.3	-0.4	-0.6	-0.5	-0.6	-0.5	-0.4	-0.4	-0.4	-0.3	0.1	0.8	1.1
41.0	-1.1	-1.0	-1.4	-1.3	-1.3	-1.4	-1.4	-1.4	-1.4	-1.5	-1.8	0.5	0.9
42.0	-1.5	-1.5	-1.7	-1.9	-1.8	-1.9	-2.1	-2.4	-2.3	-2.3	-2.9	0.1	0.5
43.0	-1.5	-1.6	-1.7	-1.8	-1.9	-1.9	-2.0	-2.2	-2.2	-2.2	-2.6	0.4	0.8
44.0	-0.6	-0.7	-1.5	-1.8	-1.7	-1.7	-1.6	-1.8	-1.7	-1.7	-1.6	1.0	1.2
45.0	0.3	0.2	0.1	0.1	-0.3	-0.3	-0.1	0.0	-0.1	0.0	-0.2	1.3	1.5
46.0	1.4	1.6	1.9	1.8	2.0	2.0	1.7	1.7	1.7	1.6	1.3	1.8	1.9
47.0	2.2	2.2	2.7	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.2	2.2	2.3
48.0	2.8	2.9	3.0	3.3	3.3	3.3	3.6	3.9	3.8	3.8	4.3	2.6	2.7
49.0	2.8	2.9	3.0	3.6	3.5	3.5	3.7	3.9	3.9	3.8	4.2	2.4	2.5
50.0	2.1	2.1	2.9	3.3	3.1	3.1	3.2	3.4	3.4	3.4	3.2	1.9	2.2
51.0	1.4	1.4	1.7	1.4	1.8	1.9	1.8	1.6	1.6	1.6	1.9	1.8	2.0
52.0	0.4	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.3	0.5	1.3	1.7
53.0	-0.2	-0.3	-0.6	-0.5	-0.6	-0.7	-0.6	-0.4	-0.5	-0.6	-1.0	1.1	1.4
54.0	-0.5	-0.6	-0.7	-0.9	-0.8	-0.8	-0.9	-1.2	-1.1	-1.1	-1.5	0.8	1.1
55.0	-0.6	-0.5	-0.5	-0.7	-0.6	-0.7	-0.8	-0.9	-0.9	-0.9	-1.0	0.9	1.3
56.0	0.3	0.4	-0.4	-0.5	-0.3	-0.3	-0.3	-0.3	-0.3	-0.4	-0.2	1.5	1.5
57.0	1.0	1.0	0.8	1.2	0.7	0.7	0.9	1.1	1.1	1.1	0.9	1.6	1.8
58.0	1.8	2.0	2.2	2.3	2.3	2.3	2.2	2.1	2.1	2.1	2.0	2.0	2.1
59.0	2.4	2.4	2.7	2.6	2.8	2.9	3.0	2.8	2.8	3.0	3.2	2.3	2.4
60.0	2.7	2.7	2.9	3.1	3.0	3.1	3.3	3.4	3.4	3.4	3.8	2.6	2.7
61.0	2.8	2.8	2.7	3.1	3.0	3.0	3.1	3.3	3.3	3.2	3.4	2.5	2.6
62.0	2.1	2.0	2.6	3.0	2.7	2.6	2.8	2.9	2.9	3.0	2.7	1.9	2.3
63.0	1.3	1.4	1.6	1.4	1.8	1.8	1.7	1.4	1.5	1.5	1.8	1.8	2.1
64.0	0.5	0.4	0.3	0.2	0.4	0.4	0.5	0.4	0.4	0.5	0.8	1.4	1.7
65.0	-0.1	-0.1	-0.3	-0.2	-0.4	-0.4	-0.3	-0.1	-0.2	-0.3	-0.5	1.1	1.5
66.0	-0.4	-0.4	-0.5	-0.6	-0.5	-0.6	-0.8	-1.0	-0.9	-0.9	-1.2	0.9	1.2
67.0	-0.6	-0.6	-0.5	-0.7	-0.6	-0.6	-0.7	-0.9	-0.8	-0.7	-1.0	0.9	1.3
68.0	0.0	0.0	-0.6	-0.7	-0.6	-0.5	-0.5	-0.5	-0.5	-0.6	-0.5	1.2	1.4
69.0	0.4	0.3	0.2	0.5	0.0	0.0	0.2	0.3	0.3	0.4	0.3	1.2	1.6
70.0	1.1	1.2	1.3	1.3	1.3	1.4	1.3	1.3	1.3	1.1	1.0	1.5	1.7

Time Hours from 78020501 UTC / Water Level (m) NGVD

Station	1	2	3	4	5	6	7	8	9	10	11	12	13
71.0	1.4	1.5	1.8	1.7	1.8	1.9	1.8	1.6	1.7	1.8	1.9	1.6	1.9
72.0	1.7	1.7	1.8	2.0	1.8	1.8	2.0	2.2	2.1	2.1	2.5	1.7	2.0
73.0	1.6	1.7	1.5	1.8	1.7	1.8	1.9	2.1	2.1	2.0	2.2	1.7	1.9
74.0	1.1	1.0	1.5	1.7	1.5	1.5	1.6	1.6	1.6	1.7	1.6	1.4	1.7
75.0	0.7	0.8	0.9	0.6	1.0	1.0	0.9	0.7	0.7	0.7	0.8	1.3	1.6
76.0	0.2	0.1	0.0	0.0	-0.1	-0.1	0.0	-0.1	0.0	0.0	0.1	1.0	1.4
77.0	-0.2	-0.3	-0.5	-0.4	-0.5	-0.5	-0.5	-0.3	-0.4	-0.5	-0.7	0.9	1.2
78.0	-0.5	-0.5	-0.5	-0.6	-0.5	-0.5	-0.6	-0.7	-0.7	-0.7	-0.9	0.7	1.1
79.0	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.7	-0.7	-0.6	-0.6	0.8	1.2
80.0	0.1	0.1	-0.4	-0.5	-0.4	-0.3	-0.3	-0.3	-0.3	-0.4	-0.3	1.1	1.3
81.0	0.4	0.3	0.3	0.6	0.1	0.1	0.2	0.4	0.4	0.4	0.2	1.0	1.4
82.0	0.8	1.0	1.1	1.0	1.1	1.1	1.0	0.9	0.9	0.8	0.8	1.3	1.5
83.0	1.1	1.1	1.3	1.3	1.3	1.4	1.4	1.2	1.3	1.4	1.6	1.4	1.6
84.0	1.3	1.3	1.4	1.5	1.4	1.4	1.5	1.7	1.7	1.7	1.9	1.5	1.7
85.0	1.4	1.4	1.3	1.5	1.4	1.5	1.5	1.7	1.6	1.6	1.6	1.5	1.7
86.0	1.0	1.0	1.4	1.5	1.4	1.4	1.4	1.4	1.4	1.5	1.3	1.2	1.6
87.0	0.7	0.8	0.9	0.7	1.0	1.0	0.9	0.7	0.8	0.7	0.9	1.3	1.5
88.0	0.3	0.2	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.3	0.4	1.1	1.4
89.0	0.0	0.0	-0.2	-0.1	-0.1	-0.2	-0.1	0.1	0.0	-0.1	-0.2	1.0	1.3
90.0	-0.2	-0.1	-0.1	-0.2	-0.1	-0.1	-0.2	-0.4	-0.4	-0.3	-0.5	0.9	1.2
91.0	-0.2	-0.1	0.0	-0.1	-0.1	-0.1	-0.2	-0.3	-0.3	-0.2	-0.4	0.7	1.1
92.0	0.0	0.1	-0.2	-0.1	-0.1	-0.1	-0.1	0.1	0.0	-0.1	-0.1	0.6	0.9
93.0	-0.1	-0.1	-0.1	0.3	0.0	0.0	0.1	0.3	0.3	0.3	0.4	0.5	0.8
94.0	0.1	0.2	0.3	0.2	0.4	0.5	0.5	0.4	0.4	0.4	0.5	0.3	0.5
95.0	0.1	0.1	0.3	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.2	0.3

APPENDIX E

Water Level at Stations 1-13 for Halloween Storm of 1991

Station	1	2	3	4	5	6	7	8	9	10	11	12	13
Time Hours from 91102813 UTC / Water Level (m) NGVD													
1.0	-2.1	-2.3	-2.6	-2.9	-3.0	-3.1	-3.2	-3.2	-3.2	-3.3	-3.6	-0.5	0.1
2.0	-1.2	-1.4	-1.7	-1.9	-2.1	-2.2	-2.2	-2.2	-2.3	-2.4	-2.6	-0.1	0.4
3.0	-0.2	-0.4	-0.4	-0.5	-0.7	-0.8	-0.8	-0.7	-0.8	-0.9	-1.1	0.4	0.8
4.0	0.8	0.7	0.7	0.7	0.6	0.6	0.7	0.7	0.7	0.6	0.8	1.0	1.3
5.0	1.5	1.5	1.6	1.8	1.8	1.8	1.9	2.1	2.1	2.0	2.3	1.4	1.8
6.0	1.8	1.8	2.1	2.5	2.5	2.5	2.6	2.8	2.7	2.7	3.1	1.5	2.0
7.0	1.5	1.6	1.9	2.2	2.3	2.4	2.5	2.5	2.5	2.6	2.9	1.4	2.0
8.0	0.7	0.8	1.0	1.2	1.3	1.4	1.5	1.5	1.5	1.6	1.9	1.1	1.8
9.0	-0.4	-0.4	-0.3	-0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.3	0.6	1.4
10.0	-1.3	-1.3	-1.5	-1.4	-1.3	-1.3	-1.3	-1.4	-1.4	-1.3	-1.4	0.0	0.9
11.0	-2.1	-2.1	-2.4	-2.5	-2.4	-2.4	-2.4	-2.6	-2.5	-2.5	-2.6	-0.5	0.5
12.0	-2.5	-2.6	-2.9	-3.0	-3.0	-3.1	-3.1	-3.3	-3.2	-3.2	-3.3	-0.8	0.1
13.0	-2.5	-2.7	-3.0	-3.2	-3.2	-3.3	-3.3	-3.3	-3.3	-3.3	-3.5	-0.7	0.0
14.0	-1.9	-2.2	-2.5	-2.7	-2.8	-2.8	-2.9	-2.8	-2.9	-2.9	-3.0	-0.4	0.3
15.0	-1.1	-1.2	-1.3	-1.5	-1.7	-1.7	-1.8	-1.7	-1.8	-1.9	-2.0	0.0	0.5
16.0	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4	-0.5	-0.4	-0.4	-0.5	-0.6	0.5	0.9
17.0	0.8	0.8	0.7	0.8	0.7	0.7	0.8	0.9	0.9	0.9	1.0	1.0	1.4
18.0	1.3	1.3	1.5	1.7	1.7	1.8	1.9	2.0	2.0	2.0	2.2	1.3	1.7
19.0	1.5	1.5	1.8	2.0	2.1	2.2	2.3	2.4	2.4	2.4	2.7	1.3	1.8
20.0	1.2	1.3	1.4	1.7	1.8	1.8	1.9	1.9	2.0	2.0	2.3	1.2	1.9
21.0	0.4	0.4	0.6	0.8	0.9	1.0	1.0	1.0	1.0	1.1	1.2	0.8	1.6
22.0	-0.5	-0.5	-0.6	-0.5	-0.3	-0.3	-0.3	-0.4	-0.4	-0.3	-0.2	0.5	1.2
23.0	-1.3	-1.3	-1.6	-1.6	-1.5	-1.4	-1.4	-1.6	-1.5	-1.5	-1.5	0.0	0.8
24.0	-1.8	-1.9	-2.1	-2.3	-2.2	-2.2	-2.3	-2.5	-2.4	-2.3	-2.4	-0.3	0.6
25.0	-1.8	-1.9	-2.3	-2.5	-2.6	-2.6	-2.7	-2.8	-2.8	-2.7	-3.0	-0.3	0.4
26.0	-1.3	-1.5	-1.8	-2.1	-2.2	-2.2	-2.3	-2.3	-2.3	-2.4	-2.7	0.1	0.7
27.0	-0.6	-0.8	-0.9	-1.1	-1.2	-1.3	-1.4	-1.3	-1.4	-1.5	-1.6	0.5	1.0
28.0	0.3	0.1	0.1	0.0	0.0	-0.1	-0.1	0.1	0.0	-0.1	0.0	0.9	1.4
29.0	1.1	1.1	1.1	1.1	1.1	1.2	1.3	1.5	1.4	1.3	1.5	1.4	1.9
30.0	1.7	1.7	1.9	2.1	2.1	2.1	2.2	2.4	2.3	2.3	2.6	1.7	2.2
31.0	1.9	2.0	2.3	2.5	2.5	2.5	2.6	2.8	2.7	2.7	2.9	1.7	2.3
32.0	1.6	1.6	1.9	2.1	2.1	2.2	2.3	2.3	2.3	2.4	2.6	1.6	2.2
33.0	0.8	0.8	1.0	1.2	1.2	1.3	1.3	1.3	1.3	1.4	1.6	1.3	2.0
34.0	-0.1	-0.1	-0.1	-0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.8	1.6
35.0	-0.9	-0.9	-1.0	-1.0	-1.0	-0.9	-0.9	-1.0	-1.0	-1.0	-1.0	0.3	1.2
36.0	-1.5	-1.5	-1.7	-1.8	-1.7	-1.8	-1.8	-2.0	-1.9	-1.9	-2.0	0.0	0.8
37.0	-1.8	-1.9	-2.2	-2.3	-2.3	-2.3	-2.3	-2.4	-2.4	-2.3	-2.5	-0.2	0.6
38.0	-1.7	-1.8	-2.2	-2.3	-2.3	-2.4	-2.4	-2.4	-2.4	-2.4	-2.5	-0.1	0.6
39.0	-1.3	-1.4	-1.6	-1.8	-1.8	-1.9	-1.9	-1.9	-2.0	-2.0	-2.1	0.1	0.8
40.0	-0.5	-0.7	-0.8	-0.9	-1.0	-1.0	-1.0	-0.9	-1.0	-1.1	-1.2	0.5	1.1
41.0	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	1.0	1.5
42.0	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.1	1.1	1.2	1.5	1.9
43.0	1.7	1.7	1.8	2.0	1.9	1.9	2.0	2.2	2.2	2.1	2.2	1.7	2.2
44.0	1.7	1.8	2.1	2.3	2.3	2.3	2.4	2.5	2.5	2.5	2.7	1.7	2.3
45.0	1.5	1.5	1.7	1.9	2.0	2.0	2.1	2.2	2.2	2.3	2.6	1.6	2.3
46.0	0.8	0.8	1.0	1.2	1.2	1.3	1.4	1.4	1.4	1.5	1.7	1.3	2.0
47.0	0.0	-0.1	0.0	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	1.0	1.7
48.0	-0.7	-0.7	-0.9	-0.9	-0.8	-0.8	-0.8	-0.9	-0.8	-0.8	-0.9	0.6	1.4
49.0	-1.1	-1.1	-1.4	-1.6	-1.5	-1.5	-1.6	-1.7	-1.7	-1.6	-1.7	0.4	1.2
50.0	-1.2	-1.3	-1.7	-1.8	-1.8	-1.8	-1.9	-2.0	-2.0	-1.9	-2.1	0.4	1.1
51.0	-0.7	-0.9	-1.2	-1.4	-1.4	-1.4	-1.5	-1.5	-1.5	-1.5	-1.8	0.7	1.3
52.0	0.0	-0.1	-0.3	-0.5	-0.5	-0.6	-0.6	-0.7	-0.7	-0.7	-0.8	1.2	1.6
53.0	0.8	0.7	0.7	0.7	0.6	0.6	0.6	0.7	0.6	0.6	0.6	1.5	2.0
54.0	1.7	1.6	1.6	1.7	1.7	1.7	1.8	2.0	2.0	1.9	2.0	2.0	2.5
55.0	2.2	2.2	2.4	2.5	2.5	2.5	2.6	2.7	2.7	2.7	3.1	2.3	2.8
56.0	2.4	2.4	2.7	3.0	2.9	3.0	3.0	3.3	3.2	3.2	3.4	2.5	3.0
57.0	2.2	2.2	2.5	2.6	2.7	2.7	2.8	2.9	2.9	2.9	3.1	2.4	3.0
58.0	1.6	1.6	1.8	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.3	2.1	2.8
59.0	0.7	0.6	0.8	1.0	1.0	1.0	1.1	1.2	1.2	1.2	1.3	1.6	2.4
60.0	-0.2	-0.3	-0.3	-0.3	-0.1	-0.1	0.0	-0.1	-0.1	0.0	0.1	1.2	2.0
61.0	-0.9	-0.9	-1.1	-1.0	-1.0	-1.0	-0.9	-0.9	-0.9	-0.9	-0.9	0.6	1.5
62.0	-1.4	-1.4	-1.6	-1.5	-1.5	-1.5	-1.6	-1.6	-1.6	-1.6	-1.7	0.2	1.1
63.0	-1.5	-1.6	-1.9	-2.0	-1.9	-1.9	-2.0	-2.1	-2.0	-2.0	-2.1	0.2	1.0
64.0	-1.3	-1.4	-1.8	-1.8	-1.8	-1.9	-1.8	-1.8	-1.8	-1.8	-1.9	0.3	1.0
65.0	-0.8	-1.0	-1.2	-1.2	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	0.6	1.2
66.0	0.0	-0.1	-0.3	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	0.9	1.5
67.0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.7	1.3	1.8
68.0	1.2	1.2	1.4	1.6	1.5	1.5	1.5	1.7	1.7	1.6	1.8	1.5	2.0
69.0	1.4	1.4	1.7	1.9	1.9	2.0	2.1	2.4	2.3	2.3	2.6	1.4	2.0
70.0	1.1	1.1	1.4	1.7	1.7	1.8	1.9	2.1	2.1	2.1	2.5	1.3	1.9

Station	1	2	3	4	5	6	7	8	9	10	11	12	13
Time Hours from 91102813 UTC / Water Level (m) NGVD													
71.0	0.4	0.4	0.7	0.9	1.0	1.0	1.1	1.2	1.2	1.2	1.5	0.9	1.6
72.0	-0.3	-0.3	-0.3	-0.2	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.5	1.3
73.0	-1.2	-1.2	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	0.0	0.8
74.0	-1.8	-1.8	-2.1	-2.1	-2.1	-2.1	-2.2	-2.2	-2.2	-2.2	-2.3	-0.4	0.5
75.0	-2.0	-2.1	-2.5	-2.7	-2.6	-2.6	-2.6	-2.7	-2.7	-2.7	-2.8	-0.5	0.3
76.0	-1.8	-2.0	-2.3	-2.5	-2.5	-2.6	-2.6	-2.7	-2.7	-2.7	-2.8	-0.2	0.5
77.0	-1.0	-1.2	-1.5	-1.7	-1.8	-1.8	-1.9	-1.9	-1.9	-2.0	-2.2	0.2	0.7
78.0	-0.1	-0.2	-0.3	-0.5	-0.6	-0.7	-0.7	-0.6	-0.7	-0.8	-1.0	0.6	1.0
79.0	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.7	0.7	0.6	0.7	1.1	1.4
80.0	1.4	1.4	1.5	1.6	1.6	1.7	1.8	1.9	1.9	1.9	2.1	1.4	1.8
81.0	1.7	1.7	2.0	2.2	2.3	2.3	2.5	2.7	2.7	2.6	2.9	1.5	2.0
82.0	1.5	1.6	1.9	2.2	2.2	2.2	2.3	2.4	2.4	2.4	2.7	1.4	2.0
83.0	0.9	0.9	1.2	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.7	1.1	1.8
84.0	-0.1	-0.1	0.0	0.0	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.7	1.5
85.0	-1.1	-1.2	-1.3	-1.2	-1.1	-1.1	-1.1	-1.2	-1.2	-1.1	-1.1	0.1	1.0
86.0	-1.8	-1.8	-2.1	-2.2	-2.1	-2.1	-2.1	-2.2	-2.2	-2.1	-2.3	-0.3	0.6
87.0	-2.2	-2.3	-2.5	-2.7	-2.7	-2.7	-2.8	-2.9	-2.9	-2.8	-3.0	-0.6	0.2
88.0	-2.2	-2.3	-2.6	-2.8	-2.9	-2.9	-3.0	-3.1	-3.0	-3.0	-3.2	-0.6	0.2
89.0	-1.7	-1.8	-2.2	-2.4	-2.5	-2.5	-2.6	-2.5	-2.6	-2.6	-2.9	-0.2	0.4
90.0	-0.9	-1.0	-1.2	-1.4	-1.5	-1.6	-1.6	-1.6	-1.6	-1.7	-1.8	0.2	0.7
91.0	0.1	0.0	0.0	-0.2	-0.2	-0.3	-0.3	-0.2	-0.3	-0.4	-0.4	0.7	1.1
92.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.2	1.1	1.1	1.1	1.1	1.5
93.0	1.6	1.6	1.8	2.0	2.0	2.0	2.1	2.2	2.2	2.1	2.4	1.5	1.9
94.0	1.7	1.8	2.1	2.4	2.4	2.4	2.5	2.7	2.6	2.6	2.9	1.5	2.0
95.0	1.3	1.4	1.7	2.0	2.0	2.1	2.2	2.3	2.3	2.3	2.5	1.3	1.9
96.0	0.6	0.6	0.8	0.9	1.0	1.1	1.1	1.1	1.1	1.2	1.4	1.0	1.7

Appendix F

Locations of All Stations Closest to Shore

Station Number	Latitude Deg. Min.	Longitude Deg. Min.
1	43 45	69 35
2	43 40	69 35
3	43 40	69 40
4	43 40	69 45
5	43 40	69 50
6	43 40	69 55
7	43 40	70 00
8	43 35	70 00
9	43 35	70 05
10	43 35	70 10
11	43 30	70 10
12	43 30	70 15
13	43 30	70 20
14	43 25	70 20
15	43 20	70 20
16	43 15	70 20
17	43 15	70 25
18	43 15	70 30
19	43 10	70 30
20	43 05	70 30
21	43 05	70 35
22	43 00	70 35
23	43 00	70 40
24	42 55	70 40
25	42 55	70 45
26	42 50	70 45
27	42 45	70 45
28	42 45	70 40
29	42 45	70 35
30	42 40	70 35
31	42 35	70 35
32	42 30	70 35
33	42 30	70 40
34	42 30	70 45
35	42 25	70 45
36	42 25	70 50
37	42 20	70 50
38	42 20	70 45
39	42 20	70 40
40	42 15	70 40
41	42 10	70 40
42	42 10	70 35
43	42 05	70 35
44	42 05	70 30
45	42 00	70 30
46	41 55	70 30
47	41 50	70 30
48	41 50	70 25

Appendix F Continued

Locations of All Stations Closest to Shore

Station Number	Latitude Deg. Min.	Longitude Deg. Min.
49	41 50	70 20
50	41 50	70 15
51	41 50	70 10
52	41 55	70 10
53	42 00	70 10
54	42 00	70 15
55	42 00	70 20
56	42 05	70 20
57	42 10	70 20
58	42 10	70 15
59	42 10	70 10
60	42 10	70 05
61	42 05	70 00
62	42 00	69 55
63	41 55	69 55
64	41 50	69 55
65	41 45	69 55
66	41 40	69 55
67	41 35	69 55
68	41 30	69 55
69	41 25	69 55
70	41 20	69 55
71	41 15	69 55
72	43 30	70 05
73	42 25	70 30

APPENDIX E

STORM DAMAGE

The following are summary descriptions of damages occurring in various communities of Massachusetts and Maine as a result of the Halloween Storm of 1991. This information is derived from: 1) reports by members of the Corps' Coastal Engineering Research Center (CERC) comprising an emergency assessment team, 2) Federal Emergency Management Agency (FEMA) Damage Survey Reports, 3) field reports made by New England Division personnel, and 4) observations made by local officials and others.

STATE OF MAINE

CITY OF SACO

The following description is a summary of FEMA's Damage Survey Report and field reports of New England Division personnel:

Many roadways suffered damages during this storm. Surf Street was totally or partially destroyed over a distance of 800 feet. Roadway and rock protection were either disturbed or washed away on Eastern Avenue and Pearl Street, while on Main Avenue and North Avenue the surface pavement was lost. Pavement also failed and was washed out at these locations. See Photos 1, 2 and 3.

The natural dune system at Camp Ellis Beach appeared to retreat approximately 5 feet. Material under the rock revetment on Island View Avenue has washed away, causing settlement. The seawall/revetment on Surf Street was damaged. The approach to the Camp Ellis pier and the pier itself were also damaged. Wave action and high tides undermined a portion of the foundation wall of the public pier. The rock revetment along the slope of the approach was eroded and settled in an irregular pattern.

Photo 1

Saco, Maine
Camp Ellis Beach bulkhead damage.

Photo 2

Camp Ellis Beach bulkhead
and house damage.

Photo 3

Camp Ellis Beach dune erosion
and stockpiled sand.

TOWN OF WELLS

The following description is a summary of FEMA's Damage Survey Report:

Flood debris (rocks, sand, gravel, and logs) was deposited on many public property sites due to the storm. Roads, parks, buildings, and other public property was also affected. Sediments were deposited on streets and in drainage systems townwide.

The roadways and parking lots of Wells also suffered extensive damage. The parking lot on the jetty side of Drakes Island was washed out and covered with sand. Pavement was washed out and failed at various locations townwide, and the subgrade and ditches were scoured in the Eastern Shore Parking lot as well. Floodwaters washed out the roadway surface of the access road to Wells Beach on Folsom Avenue. The storm deposited debris and eroded the parking area and street at Drakes Island Beach.

TOWN OF SALISBURY

The Town of Salisbury is located in the northeast corner of Massachusetts, approximately 35 miles north of Boston. Salisbury Beach is immediately north of the mouth of the Merrimack River. The following observations were made by the CERC emergency assessment team on November 26, 1991.

Ocean Street. This section is bounded on the south by Ocean Street and extends north for approximately 1000 feet. A significant amount of overwash in this area had been pushed landward during the storm. This accumulation of sediment at the upper portion of the beach has resulted in a steeper beach slope. Some emergency work has been done to clear material from the streets and move it back onto the beach. Several large buildings along this section of shoreline were constructed on piles such that they extend outward over the surf zone. The piles under each of the buildings located on the beachfront between Ocean St. and Beach Rd. have been damaged and repaired on numerous occasions in the past. Because of this, it is not possible to assess how much recent structural damage may have been caused by the Halloween Storm. There is no other shore protection seaward of the structures.

Northern Limit of Business Section. This site is bounded on the south by a fairly new building called the Pavilion. Overwashed sand had been carried landward over the beach and accumulated along the seaward side of the concrete wall which fronts the parking lot located adjacent to the Pavilion. The parking lot had accumulated approximately 4 to 6 inches of overwash sand. The beach in front of the wall was very steep in the upper portion leading to a narrow flat berm. Shore protection for the residences to the north is characterized by individually constructed concrete walls and there was some evidence of a small dune system in various places. Inland structures in this vicinity appear to have experienced only minor structural and flood damage.

Atlantic Avenue (2000 feet north of Ocean St.). A significant amount of overwashed sediment was moved landward and accumulated on the upper portion of the beach, creating a relatively steep slope. Some erosion was observed at the seaward face of the dunes; however, most of the dune system has remained intact. Structural damage to homes in this area appeared to be minor and superficial. The beach appears to be fairly flat in an area south toward the Merrimack River jetties.

Southern End of Atlantic Avenue. This section extends from the southern end of Atlantic Avenue for approximately 1500 feet northward. Dunes in this area are intact and appear in relatively good condition. There has been moderate damage to what appear to be relatively old private residences. One house which had been built on top of the dune was severely damaged. However, it was not apparent that all of this damage can be attributed to the Halloween Storm. A badly weathered and

deteriorated timber and rock bulkhead is located at this house. Some of the structures observed, particularly in the business section along the beach, are vulnerable because they are relatively old and are located very close to the active surf zone. Several of these large buildings currently extend over the water at high tide. These buildings were built on piles, which has undoubtedly prolonged their longevity.

PLUM ISLAND - CITY OF NEWBURYPORT & TOWNS OF NEWBURY, ROWLEY, IPSWICH

Plum Island is located on the east coast of Massachusetts in the City of Newburyport and the Towns of Newbury, Rowley, and Ipswich. Its northern end is at the mouth of the Merrimack River about 4 miles south of the Massachusetts-New Hampshire boundary. This site was visited by the CERC emergency assessment team on December 4, 1991.

The first site visited was in the vicinity of the rock groin at 3rd Street. There was evidence of emergency work which had been done to push overwashed sand from the streets back onto the beach. Homes in this area have been built close to the dune line and are fronted by relatively healthy and substantial dunes. There was minimal to no damage to the residences. Snow fence had been placed along a major portion of the dune system. The beach is relatively wide and characterized by beach cusp formations to the north and south.

To the north of the first site, the beach and dune system is very similar. Even at high tide, a relatively wide beach was apparent with a healthy dune system fronting the residences along the beachfront.

Further north, the dune system is even more extensive, however, a breach of the dunes did occur in this area. See Photo 4. No residential development existed in the immediate dune line. According to a local resident, this was a weak point in the dune system due to its unauthorized use as a beach access route for vehicles. The breach had already been closed with sand that had overwashed landward. See Photo 5. The beach in front of these dunes is relatively wide, and flattens out northward toward the Merrimack River jetties.

Photo 4

Plum Island, Massachusetts
Dune blowout.

Photo 5

Dune blowout of Photo 24 has
been repaired.

CITY OF GLOUCESTER

The City of Gloucester is located on the east coast of Massachusetts, approximately 30 miles northeast of Boston. The section of coastline investigated by the CERC emergency assessment team began at the southern end of Gloucester up to and including portions of Rockport. Only selected locations of this coastline with known property damage were visited. The following observations were made by the CERC emergency assessment team on December 4, 1991.

Shore Drive near Magnolia Point. The rock coast in this area has extensive rock outcrops extending into the waterline. A section of seawall, built on top of the rock, sustained severe damage apparently due to wave impact. Behind this seawall, a section of road pavement was damaged and in need of repair. The seawall and roadway appeared to be at a relatively high elevation. See Photo 6.

Stage Fort Park. Several sections of the stone wall at this park sustained moderate wave impact damages. It appeared that this wall was not built for wave/flood protection. The beach consisted of cobbles and rocks. Behind the wall, there is a large open grass field which had been littered with overwashed cobble and assorted debris.

Atlantic Road south of Moorland Road. A section of roadway sustained severe damage and at one section traffic was limited to one lane. The road appeared to be at a relatively high elevation and emergency repair work was already underway. See Photo 7.

The following is a summary of FEMA's Damage Survey Report for Gloucester:

Various roadway surfaces were washed out by the floodwaters of the storm. Pavement washed out and failed in various locations, and subgrade and ditches were scoured at Hesperus Road, Shore Road, Atlantic Road, and at the Eastern Point parking lot. Concrete and asphalt sidewalks needed to be replaced on Stacy Boulevard and Nautilus Road. Sections of the Lucy Davis seawall, along with the seawalls at Magnolia Harbor and Cressy Beach needed repair due to wave action. The breakwater at Lane's Cove again failed as it did during Hurricane Bob and the 1978 Blizzard. Floodwaters also caused debris to be deposited on roads, in parks, buildings and other public property in various locations close to the shore.

A ramp at Half Moon Beach needed repairs due to damage caused by erosion during the storm. Snow fencing, boardwalks, a wood roadway, and asphalt parking lots were destroyed at Good Harbor and Wingaersheeck Beaches. The Fort Square Playground, Magnolia Pier structure, ramps and floats in Lane's Cove, and a foot bridge in Good Harbor were all damaged by the storm.

Photo 6

Gloucester, Massachusetts
Erosion of Shore Drive.

Photo 7

Pavement and debris along
Atlantic Road.

TOWN OF ROCKPORT

The Town of Rockport is located on the east coast of Massachusetts, approximately 30 miles northeast of Boston and north and east of Gloucester. The section of coastline investigated by the CERC emergency assessment team began in Gloucester and extended north to the Pigeon Cove area of Rockport. Only selected locations of this coastline with known property damage were visited. The following observations were made by the CERC emergency assessment team on December 4, 1991.

Long Beach. This beach has a concrete seawall, approximately 3,000 feet long which protects a rather dense concentration of houses immediately behind the seawall. There was no noticeable damage to the concrete wall, however, a section of metal railing at the top of the seawall was badly damaged. The houses behind the seawall sustained moderate to severe damages. The beach fronting the seawall appeared flat and narrow. See Photos 8 and 9.

Cape Hedge Beach. In contrast to Long Beach, Cape Hedge Beach is a cobble beach which had been flattened somewhat by the Halloween Storm. The public parking area behind the cobble berm was totally covered by the cobble. Access to the beach is limited to an unpaved road. Several houses located approximately 200 to 300 feet behind the public parking area sustained minor to moderate damage.

Pigeon Cove Seawall. The massive stone seawall constructed on the peninsula protecting a private fishing industry was apparently not damaged; however, a short stone breakwater at the end of the seawall and entrance to the cove suffered minor damage at its two ends.

The following is a summary of FEMA's Damage Survey Report for Rockport:

Floodwaters deposited sediment on various roadways and public areas such as Front Beach, the Penzance Road Area, and the South St. Public Landing. High water also washed out pavement, caused embankment failures, and scoured the subgrade and ditches of several roadways. Marmion Way, the Loblolly Cove area, and the Bear Skin Rotary Roadway were all damaged in the storm. The Seaview Parking Lot required the removal of stones and the replacement of its gravel surface, while the sanitary building at the same location was damaged beyond repair.

Riprap was displaced at Back Beach, Pigeon Cove, Old Garden Beach, Doyle Cove, Atlantic Path, Long Beach, and the Old Harbor Seawalls. The boat ramp at Dock Square was completely destroyed. The Star Island Park embankment and Bradley Wharf both needed fill to repair the damages that occurred during the storm. Three areas of the Steep Bank Landing Park eroded and need to be replaced. Granite blocks, steps and benches were displaced at Lumber Wharf and Middle Wharf. The granite wall at Front Beach also needed rebuilding. The riprap at the nose of the Granite Pier was displaced by wave action during the storm, and boat ramps were undermined. Heavy seas and surge also caused the displacement of stones at the Outer Breakwater.

Photo 8

Rockport, Massachusetts
Long Beach seawall damage.

Photo 9

Long Beach backfill loss.

Recreational facilities at Long Beach, Pigeon Cove, T-Wharf, and Granite Pier were also damaged by the storm. Two pedestrian footbridges were in need of replacement, a deck and parking lot surface were destroyed, and storm surge overtopped the bulkhead and scoured out the material behind the seawall at Long Beach. The boathouse structure at Thatchers Island was also damaged beyond repair. The Whistle House and elevated walkway at the same location both suffered severe damage. The restrooms, bathhouse, and parking and ramp area at Front Beach all suffered extensive damage.

CITY OF REVERE

The City of Revere "Point of Pines" community is located on the east coast of Massachusetts approximately 10 miles north of Boston. The section of coastline examined by the CERC emergency assessment team was immediately north of the Federal beach nourishment project recently completed at Revere Beach. This site was visited by the CERC emergency assessment team on November 20, 1991.

Dune System. Notable degradation of the dune system was observed along the extreme northern end of the Point of Pines beach. A significant amount of the material removed from the dune was carried landward and deposited in the streets and yards of residents immediately landward of the dunes. Clean up efforts used this sand to rebuild portions of the existing damaged dunes to the approximate crest height of the preexisting dunes.

Seawalls. Two sections of seawall were observed at the north end of the project. The concrete seawall constructed in the 1960's did not experience noticeable structural damage. The 1960's seawall abuts a second seawall which was built in 1957 by placing precast concrete sections over an existing rubble foundation. The precast portion of the structure did not sustain noticeable damage, however, significant scour and undermining of the base of the structure was observed. It is not known if all of the observed damage occurred as a result of the Halloween Storm. Some settling of the asphalt apron on the landward side of both seawalls was also observed. This settling was apparently due to consolidation and loss of backfill material. Additionally, several large cavities were observed in the asphalt apron behind the seawalls.

Beach. Aside from the scour/undermining problem with the 1957 seawall noted above, no significant problems were observed with the beach fronting the seawalls. In fact, some accumulation from the Federal beach nourishment project at Revere Beach was evident. This project included restoring approximately 13,000 feet of beach requiring about 800,000 cubic yards of sand. Observations show that the beach immediately north of the nourishment project had been raised 6-7 feet, apparently derived from the Revere Beach fill. A minor accumulation of sand (approximately 1-2 feet) was also observed at the northern end of the 1960's seawall. This was also apparently derived from the Revere Beach sandfill and nourishment project. The Federal beach nourishment project at Revere Beach prevented an estimated $3 million in damages to nearly 150 private and public buildings and facilities. The reconstruction of the beach allowed storm waves to break approximately 100 feet from the existing seawalls, preventing the seawalls from being overtopped and causing serious flooding.

The following is a summary of FEMA's Damage Survey Report for this community:

Sediments were deposited on Siren Street, Mermaid Avenue, Coral, Pebble, and Triton streets, and other locations citywide. Sections of Point of Pines and the Beachmont areas were covered with rocks, sand, gravel, and logs. Basins, manholes, and the storm drainage network in these areas also required cleaning of sand, stone, and other ocean debris after the storm.

The armor stone wall along the lower reach of Revere Beach required repair because of damages from the storm. The tide gate regulating discharge into Diamond Creek needed to be replaced because the hinges, gasket, headwall, and wingwall were in varying states of wear, damage, and deterioration. The pump station at Point of Pines also suffered damages due to the storm. The seawall area along Rice Avenue required the restoration of the apron, the underlayers, and the protective riprap.

Additional Remarks:

There was extensive coastal flooding due to tidal surges in the Broadsound Avenue area of Roughan's Point. Floodwaters inundated many homes on Broadsound Avenue and denied access to many other residents. Some local residents claimed that the storm was more severe than the Blizzard of 1978. Interior flooding also occurred along Route 107 in both the Point of Pines and Diamond Creek areas.

Nahant Beach and Little Nahant Beach are located in Nahant, Massachusetts, approximately 8 miles northeast of Boston. The section of coastline was examined by the CERC emergency assessment team and covers the entire length of the Nahant Beach Parkway, which is approximately 10,000 feet in length. This site was visited by the emergency assessment team on December 4, 1991.

Both Nahant Beach and Little Nahant Beach, east of the Nahant Beach Parkway, appeared narrow and flat. The beaches are composed primarily of fine sand, however, cobbles and rocks are apparent on the upper portion of the beach in some areas. Damage observed along the two beaches was minimal. The southern end of Little Nahant Beach is protected by a rock revetment. One of the two Coast Guard buildings located at the center of Little Nahant Beach suffered minor damage. The sidewalk east of the Coast Guard parking area was severely damaged. No significant damage to the dune system was apparent along the shoreline. The entire section of the coastline had a relatively low elevation, and there is substantial visual evidence of flooding (overwashed sand, rock, and floating debris) in this area as a result of the storm. At the time of this visit, local clean-up efforts were ongoing in the parking and beach areas at the north end of the parkway. Some of the overwashed sand had been cleaned from the asphalt areas and stockpiled for future repair work. The pavement of the parkway generally appears lower than the dunes; however, it is protected by concrete walls approximately 2 feet in height on both sides of the traveled way. No damage to the parkway pavement and its protecting walls was observed. The areas inspected appeared to have sustained only minimal damages.

The following is a summary of FEMA's Damage Survey Report:

On Willow Road, the Halloween Storm destroyed a gravel protective berm built of beach material. At other locations on the same road, an armored revetment protecting the road, a seawall, and a gravel revetment were damaged. Two sections of the masonry seawall and one section of a boat parking area on Wharf Street were destroyed by the storm. On Nahant Road and Marginal Road, shore side bluffs were severely eroded by the storm. Roads and public walking trails were threatened by the collapse of these structures. See Photo 10.

The storm also destroyed the berm on Nahant Road, scattering stones across the neck. The stone masonry wall and fence system on Castle Road were totally destroyed by the storm. Flooding also lifted and twisted the main wharf at Town Wharf, destroying a large float and ramp. The parking lot at the golf course on Willow Road also suffered damages due to the storm.

Photo 10

Nahant, Massachusetts
Damage to seawall.

TOWN OF HULL, NANTASKET BEACH

Nantasket Beach is located in the Town of Hull, on the east coast of Massachusetts, approximately 20 miles south of Boston. The section of coastline examined by the CERC emergency assessment team is bound on the north by Allerton Point and on the south by the concrete seawall in the vicinity of Water Street. The site was visited by the CERC emergency assessment team on November 20, 1991.

Seawall. A short section of seawall was examined at the south end of the site. The concrete seawall constructed in the 1950's did not sustain noticeable structural damage.

Dune System. Notable degradation of the dune system which existed prior to the storm was observed along the entire length of beach from the intersection of Manomet Avenue and Beach Avenue to the revetted section at the base of the bluff at Allerton Point. See Photos 11 and 12. In numerous cases the dunes suffered severe erosion. A significant amount of material removed from the dunes and the beach was carried landward and deposited in the streets, yards, and houses behind the dunes. The most severe problems existed along the south end in the vicinity of Phipps Street, and from L Street north to Allerton Point. Street cleaning efforts used this sand to rebuild portions of the dune system. Numerous cases were observed where private parking areas intruded into the natural dune system.

Beach. The beach in front of the seawall was very flat. Some loss of this beach may have occurred as a result of the storm. The beach in front of the dune system was also very flat up to Adams Street, where more relief was evident. Based on visual observations, the assessment team felt that a significant amount of beach sediment was transported landward beyond the dune line.

Below is a summary of damages obtained from FEMA's Damage Survey Report for this community:

Flood debris was deposited on various roadways, catch basins, and drains throughout the town. Floodwaters also damaged the bituminous roadway on Beach Avenue and several other locations townwide. Two valve flaps on the Duck Land and Ocean Avenue outfall pipes were destroyed and washed away due to storm actions. At the town landing on James Avenue, a wood platform with handrails was destroyed by the storm. Stairs to the beach and a dock at Gunrock Beach also needed to be replaced, as well as sixteen sections of dune/beach ramps along Beach Avenue.

Storm surge and waves overtopped the bulkhead on Nantasket Avenue and scoured out the material behind the seawall at Gunrock Avenue. Flooding damaged the existing bank protections and seawalls at various locations throughout the town. The water pollution control facility and pumping stations on Nantasket Avenue also suffered extensive damages. The Sullivan Play area at Pemberton Beach was also damaged by the storm.

Photo 11

Hull, Massachusetts
Loss of dune and pavement.

Photo 12

Dune rebuilding on Nantasket Beach.

TOWN OF SCITUATE

The Town of Scituate is located on the east coast of Massachusetts approximately 20 miles southeast of Boston. The section of coastline examined by the CERC emergency assessment team was bounded on the north by the Minot seawall and on the south by Humarock Beach. A total of 13 sites in this area were visited by the emergency assessment team on November 21, 1991.

Minot Seawall.

The seawall at Minot is a massive concrete structure, most of which was renovated in 1972. The northern 100 yards of the seawall has a crest elevation which is 2.5 feet lower than the crest of the adjoining section to the south. The southern segment is further protected from incident waves by large stones placed against the seawall and by a low "wave-tripping" breakwater approximately 25 feet seaward of the seawall. Neither section of the seawall experienced notable structural damage although the wave tripping breakwater did have a minor breach at one location. Conversations with local residents indicated that both sections of the seawall were frequently overtopped by waves during the storm. One resident stated that those waves which were not tripped by the breakwater during this storm rolled over the pooled water between the seawall and the breakwater and then smashed against and over the seawall into the streets.

Surfside Road.

This site has an essentially continuous seawall which is characterized by varying construction types and toe protections. Numerous houses behind the seawall were severely damaged by waves which overtopped the seawall. Of the seawall sections observed, no structural damage and only minor toe scour/undermining were apparent.

Shingle Beach (vicinity of Seagate Circle and Mann Hill Rd).

An extensive cobble berm exists immediately south of Surfside Road at this site. The highest portion of the berm fronts the southern end of Musquashicut Pond, and approximately 15 homes are located in a small development on the west side of the pond. The pre-storm elevation of the berm from information provided by the Town of Scituate had a crest elevation of 19.3 feet NGVD. Essentially, the Halloween Storm moved berm material landward and reduced a large portion of the berm's crest elevation by approximately 4 to 6 feet. To the south of the cobble berm is a row of 4 houses which are built on piles. These houses experienced minor to moderate damage, including varying amounts of damage to their septic systems. Houses previously situated in this area were completely destroyed in the Blizzard of 1978. The storm caused severe overwash of the cobbles onto Mann Hill Road and into the grassy marsh area (approximately five feet of material in the road).

Quick post-storm elevation measurements by New England Division showed that the cobble berm at Shingle Beach had been significantly reshaped by the storm.

Oceanside Drive near 2nd Avenue.

Homes along this section of shoreline are protected by a concrete seawall with a cobble beach in front of the structures. As a result of the storm, the cobbles were pushed up against the seawall and resulted in a steep accumulation of materials.

Oceanside Drive near 6th Avenue.

This section of shoreline is fronted by a large concrete seawall. Several large cracks which may have occurred as a result of the storm were observed in the seawall. Severe undermining/erosion occurred on the landward side of the seawall, and may have significantly weakened the structure. See Photo 13. A large amount of cobble overwash had been deposited on the landward side of the structure. A storm drain system was apparently damaged by backflow (through the ocean outflow pipe) due to the dramatic changes in hydraulic head associated with the storm waves. This backflow had caused the manhole cover and concrete pipe to fail. Subsequently, water began to flow from the failed manhole and formed a channel which then ran along the landward side of the seawall and resulted in severe undermining and erosion. Undermining of the seawall near 6th Avenue has rendered it vulnerable to additional structural deterioration by future storm events. Additionally, large cracks in the seawall and loss of backfill material have also degraded the structural integrity of the structure.

Oceanside Drive near 11th Avenue.

A concrete seawall and cobble beach system, similar to other sites visited in Scituate, exists at this site. The cobbles had been pushed landward toward the seawall, and significant overwash was evident landward of the seawall. The beach and seawall structure were in relatively good condition. Seawalls examined at this site did not sustain noticeable structural damage.

Turner Road near Scituate Avenue.

Beachfront homes in this area sustained severe damage, with numerous dwellings damaged beyond repair. A concrete seawall which appeared to be in relatively good condition exists along this stretch of shoreline. Seawalls examined at this site did not sustain noticeable structural damage.

Lighthouse Point.

The only access route for Lighthouse Point appears to be relatively well-protected and stable. Moderate damage occurred to the rock revetment in front of the lighthouse and parking lot. The lower portion of the

Photo 13

Scituate, Massachusetts
Loss of backfill material at
seawall near 6th Ave.

revetment appears to be relatively sound and did not appear to suffer significant storm-related damage. Some rocks from the upper portion of the revetment were moved landward onto the street and parking lot. The seawall immediately north of this revetment suffered minor damage caused by flanking of the seawall due to wave action. The north jetty at Scituate Harbor did not appear to suffer significant damage and remains functional. No observations were made for the south jetty.

Edward Foster Road Between First Cliff and Second Cliff.

This site was composed of a number of residences fronted by a concrete seawall. A section of shoreline exists where the seawall is approximately 3 feet lower than the adjacent seawalls; however, there are no residences behind this section. A significant amount of sand had been pushed against the seawall, apparently by wave action. Some sand had also been overwashed into the streets and yards of the residences. Seawalls examined at this site did not sustain noticeable structural damage.

Peggotty Beach.

This area is located between Second Cliff and Third Cliff along Town Way. Surface elevations on Town Way range between 8 and 11 feet NGVD. A massive stone seawall exists just to the south of this area. The first house immediately north of the seawall was completely knocked off its foundation and damaged beyond repair. See Photo 14. Northward, the first row of houses along the shoreline, which were constructed on piles, suffered only minor to moderate damages. See Photo 15. The second row of houses, across Town Way, suffered more severe damage. Cobble overwash (approximately 3 to 4 ft. in depth) occurred in the vicinity of this second row of houses. The beach in this area is relatively flat and narrow. See Photo 16. No dune system or shore protection exists along Peggotty Beach, and there is no indication that such protection existed prior to the storm.

Dickens Row.

The major feature at this site is a massive stone revetment. It appears that approximately 35 feet of the northern end of this structure was dislocated. Southward, the structure was also damaged in two additional locations.

The massive stone seawall fronting this area did sustain some damage.

Humarock Beach Area.

Humarock Beach is a cobble and sand beach which narrows northward toward Fourth Cliff. Shore protection in front of the residences along Humarock Beach is varied and ranges from no protection to dunes to individually constructed concrete bulkheads. Beach front homes along most of the shoreline experienced moderate to severe damage; the second row of dwellings also experienced moderate damage and flooding. Photos 17 and 18

Photo 14

Loss of house on foundation, Peggotty Beach.

Photo 15

House on pilings, Peggotty Beach.

Photo 16

Cleanup operations on Peggotty Beach.

Photo 17

Collapsed houses at Humarock Beach.

Photo 18

House on piles suffered only minor damage, Humarock Beach.

illustrate the differences in severity of damages between houses on piles and those on at-grade foundations. The houses in Photo 17 were essentially destroyed as compared to the house in Photo 18 which received only minor damage. Significant overwash occurred in the yards and streets throughout the entire region.

Some of the protective structures built by local individuals were damaged by the Halloween Storm and are susceptible to additional damages. Several "weak" points exist along Central Avenue due to the low elevation and narrow beach width. In general, the northern stretch of Humarock Beach is most vulnerable to further damage because the beach is narrower here, and consequently there is less of a buffer zone when subjected to wave attack.

Fourth Cliff.

This is an eroding cliff which experienced increased erosion and undercutting at the base during the storm. The property affected by this erosion is a recreational facility owned by Hanscom Air Force Base. This area adjoins a rock revetted area which was installed by local residents south of the cliff.

Additional Remarks. The landward transport and accretion observed at numerous locations in this area is in contrast to sediment transport patterns usually associated with most winter storms. Interpretation of available data indicates that this is likely due to the unusually long period waves which characterized this storm. Short period waves typically break in the surf zone, thus expending much of their energy. Waves of longer periods can move further landward before breaking. The net effect is that significantly more energy and seawater volume is driven into the nearshore. This is manifested by increased wave runup and higher water levels in the nearshore zone as well as shoreward transport of materials in the nearshore/surf zones. Although severe damage to the residences behind seawalls caused by wave overtopping was observed throughout the community of Scituate, only one of the well-designed/engineered seawall systems sustained structural damage. Although damage to residences protected by these seawalls was extensive, the damage most assuredly would have been even more devastating without the seawalls. The beaches in this area are generally narrow and low.

The following is a summary of FEMA's Damage Survey Report for the Town of Scituate. Photos 19, 20, and 21 show various examples of the Halloween Storm's destructive power throughout Scituate.

Rocks, sand, and gravel were deposited on several roads and public property in the shore areas of Scituate. Glades Road, Surfside Road, Egypt Avenue, Oceanside Drive, Seaside Avenue, Oceanside Avenue, and Turner Road were all inundated with debris. Sediments were also deposited on Edward Foster Road, the Peggotty Beach Parking Lot, the Lighthouse parking area, Town Way Extension Road, Central Avenue, nine marshlands throughout town, and various other coastal areas.

Photo 19

Severe shoreline damage.

Photo 20

Shoreline damage and debris removal.

Photo 21

Damaged houses.

Flooding damaged bituminous roadways and pavement in several areas throughout town. Glades Road, Tilden Avenue, Egypt Avenue, Oceanside Drive, Rebecca Road, Town Way Extension Road, Dickens Row, the access to Humarock Beach and various other locations were all damaged by the elevated storm water. Floodwaters caused the loss of sidewalks on Edward Foster Road and Glades Road, as well as the erosion of two grassy areas behind a seawall on Glades Road.

High water also damaged several seawalls and revetments along the coastline. Floodwaters carrying debris caused seawalls to chip and crack at several locations on Glades Road. Riprap and stone slope protections were damaged at Glades Road, Scituate Lighthouse, Surfside Road, 3rd Cliff, Driftway Road #3, and the headwall at Bailey's Causeway.

Many recreational facilities were also damaged along the coastline. The stairway to the beach off Glades Road was battered extensively by the tidal surge. Sidewalks, fencing, a drinking fountain, and a bench in the lighthouse area were destroyed by floodwaters carrying debris. Eleven floats at the Cole Parkway Marina broke away from their moorings and were left at various locations throughout town. Ramps needed to be relocated and gangways and a marina dock as well as other recreational facilities needed to be replaced due to damages at the Cole Parkway Marina.

Duxbury Beach is located on the east coast of Massachusetts approximately 40 miles south of Boston. The project area consists of a recreational beach and dune system and three residential communities. The first community is part of the town of Duxbury and is located north of the recreation beach. The other two, Gurnet Point and Saquish Head, are located to the south of Duxbury beach. These sites were visited by the CERC emergency assessment team on November 25, 1991.

Dune System. Numerous washthroughs were observed along the stretch of shoreline which ran from the recreational pavilion at the north end to the southern portion bounded by the Gurnet Point community. See Photo 22. Overwash sand had been used to repair breaches in the dune system during initial cleanup and rebuilding of the beach. See Photo 23. Remedial efforts concentrated on restoring the damaged dunes to previous conditions by using surviving adjacent sections. In addition to replenishing damaged segments of the dune system with overwash sand, extensive efforts were underway to reconstruct snow fencing for the purpose of beach preservation. Based on aerial and ground-based photographs, the dune system which existed prior to the storm was heavily vegetated and generally in very good condition. The total length of the dune system examined was approximately 20,000 feet. Approximately 1/3 of this amount sustained significant damage and the waves broke through the dunes in numerous locations along the length of the shoreline. On the southern part of Duxbury Beach, sand had overwashed into the salt marshes. The beach in front of the dune system was very flat, and showed evidence of landward migration beyond the dune line.

Gurnet Point and Saquish Head Communities. Although the communities of Gurnet Point and Saquish Head are part of the Town of Plymouth, they are addressed in this summary since they are located at the extreme southern end of Duxbury Beach. Approximately 290 residences are located in these two communities south of the Powder Point Bridge. These communities were apparently sheltered from the majority of severe wave attack and only minor damage to the residences was observed. Access to the beach area and these communities south of Powder Point Bridge is limited to a single lane, sand and gravel road running parallel to the dunes. The storm had eroded portions of the road and in other places the road had been covered with up to 1 foot of overwash sand.

North of the Duxbury Beach Pavilion. The Duxbury Beach pavilion/bathhouse located north of the Powder Point Bridge sustained significant structural and flooding damage. The three houses located just north of the pavilion were severely damaged in the storm, two of them beyond repair. These houses were still located in the dune and snow fence system. A developed section of the beach begins to the north of these houses. The residences in this area (along Ocean Road North) are fronted by a concrete seawall which was constructed in the 1950's. This seawall did not experience noticeable structural damage. Many of the residences located immediately behind the seawall were subjected to direct wave attack which overtopped

Photo 22

Duxbury, Massachusetts
Significant dune erosion on
Duxbury Beach.

Photo 23

Sand overwash on Duxbury Beach.

the seawall, and sustained significant structural and flood damage. There was little evidence of a substantial prestorm dune system in this area and the beach in front of the seawall in the northern part of this area was very flat. Some loss of this beach may have occurred as a result of the storm.

Additional Remarks. In addition to its recreational value, Duxbury Beach provides protection from direct wave attack during extreme events to communities to the west and southwest of Duxbury Bay. A healthy dune system at Duxbury Beach is critical and essential for long-term shoreline protection and flood mitigation of these communities. Although survey data for the access road along Duxbury Beach was not available at the time of this visit, observations indicate that selected sections of the road may also be vulnerable to flooding from the Duxbury Bay side. Local residents indicated that the beach and dune system had survived Hurricane Bob quite well. In fact, because Hurricane Bob had come from the south during a low tide, sand had actually been brought shoreward and increased the beach width. As evidenced by pre-storm profile data, as well as extensive aerial and land-based photography, the dune system and beach have been very well maintained and were in quite good condition prior to the Halloween Storm.

The following is a summary of FEMA's Damage Survey Report for this town:

Sediments were deposited on several town rights of way, in parks, buildings, and other public property throughout Duxbury. Floodwaters washed out the roadway surface, fill, and aggregate material on Ocean Road, Lewis Court Road, Hummock Street, E. Marginal Road, and Pine Street. The sluice gate on Ocean Road North and Bay Avenue was destroyed by the tidal surge and wave action. Several water and sewer lines throughout the town required repair due to tidal surge and wave action.

TOWN OF PLYMOUTH

Plymouth is located on the east coast of Massachusetts approximately 35 miles south of Boston. The sites visited by the CERC emergency assessment team included White Horse Beach, Priscilla Beach, and Plymouth Beach and took place on December 2, 1991.

White Horse Beach. The first site visited was just south of Homer Avenue adjacent to the revetted outlet of Bartlett Pond. This is a relatively unprotected section of shoreline. To both the north and south (toward Manomet Point), the backshore areas are protected by a stone revetment. Several residences were severely damaged and numerous others were moderately damaged. The beach in this area is relatively wide and flat, and there is no evidence of a dune system. A substantial amount of beach sand was overwashed landward into the yards and streets. Local remedial efforts were observed where sand was being removed from a parking lot and returned to the beach to form a protective berm. The masonry revetment further north on White Horse Beach experienced some undermining of the backfill and collapsed on the southern end. The revetment along a major portion of White Horse Beach is nearly continuous but varies by type of construction and amount of damage. There was also erosion of the high dune due to flanking of the revetment at the northern end of White Horse Beach.

Priscilla Beach. The northern area just south of Rocky Point was the first site visited at this beach. A large masonry stone revetment protects several residences in this area and there is a relatively wide beach here. However, according to local residents, several feet of sand was lost from in front of the structure. Priscilla Beach is characterized by different types of shoreline protection ranging from no protection to various types of revetment. Damage to these revetments ranged from minor to moderate. Most of the locations where there was no revetment experienced landward erosion of the face of the dunes ranging from 5 to 15 feet. The most severe area of bluff erosion was approximately 100 feet south of Wellington Road.

Plymouth Beach. The entire length of Plymouth Beach was observed, except for the northernmost 500 feet. The bathhouse at the entrance to the beach was severely damaged. The stone revetment which protects Plymouth Beach did not appear to be damaged. Plymouth Beach experienced significant overwash and cobbles had also washed up onto the dunes.

The following is a summary of FEMA's Damage Survey Report for Plymouth:

Flood debris (rocks, sand, gravel, and logs) was deposited on roads, in parks, buildings, and on other public property. The Plymouth Beach/Eel River area, Bartlett Brook, Winter Street, and Long Beach were all affected by this debris. Wave action and tidal surge caused the drainage outlet at Water Street to block and back up. Embankment failure occurred at the Winter Street drainage outlet and surrounding slope. Floodwaters

also damaged the stone slope protection and filter of the Warren Cove revetment. Wave and tidal action also washed out approximately 100 feet of drainage line at Fisherman's Landing.

High winds also caused damage in Plymouth. A tree fell on the Clifford Bridge, causing minor damage. Shingles on the fire station roof were blown off by the winds. Gutters were also damaged at the North Plymouth Fire Station. One utility pole service mast at the Nelson Street Recreation Area was also blown over due to high winds.

Portions of the Plymouth Beach bathhouse and the Nelson Street bath house were both destroyed due to wave action. The stone retaining wall in front of the tennis courts and portions of the bituminous concrete parking lot were destroyed by wave action at the Nelson Street bathhouse. Tidal surge and wave action washed out gravel, bituminous concrete and fill at the Plymouth Beach Parking Lot. A chain link fence and car barrier posts at the Plymouth Beach recreation area were damaged by debris that was carried by the surge and wave action. Roof shingles on the entrance shack were blown off, two utility poles, one light, and electrical conduits were destroyed. In addition, ramps and platforms at the parking facility needed to be repaired. The snow fence at the recreational facilities at Long Beach was damaged by the storm. Floodwaters also deposited sediments in the Ellisville Channel at Ellisville Harbor, significantly reducing channel capacity.

The areas of Sandwich and East Sandwich are located on the east coast of Massachusetts approximately 50 miles south of Boston and just south of the east entrance to the Cape Cod Canal. The section of coastline examined by the CERC emergency assessment team consisted of Town Beach, Spring Hill Beach, and East Sandwich Beach and were visited on December 2, 1991.

Town Beach. The section of Town Beach immediately south of the Cape Cod Canal and continuing southward for approximately 2 miles was assessed. Only minor damage to residences and some minor loss of the dunes in this area was evident. An extensive rock groin field has compartmentalized beach material, affording a measure of backshore protection in this area.

Spring Hill Beach. A groin field similar to that observed at Town Beach exists along the entire length of Spring Hill Beach. Notable degradation of the pre-storm dune system was observed along the northern end of the beach. Average loss of dune width in this area was approximately 5-10 feet, (as measured from what appears to be the previous toe to landward extent of loss) with as much as 25 feet eroded at a location north of the intersection of Salt Marsh Road and Foster Road. Numerous houses which had been built on top of the dunes sustained significant structural and flood damage. Photo 24 shows the consequences of building houses on top of dune systems. In many cases, homeowners had joined efforts to make emergency repairs to damaged dunes by placing sand against the eroded sections of dunes. Generally, the pre-storm dune system suffered varying degrees of erosion. However, contrary to previously investigated sites, material lost from the dunes was not carried landward as overwash. Significant sand accumulations south of this area (the south end of East Sandwich Beach) indicate that sand lost from the dunes was likely moved southward. Only minor damage was observed at the southernmost portion of this beach.

East Sandwich Beach. A groin field similar to that observed at Town Beach and Spring Hill Beach exists along the entire length of East Sandwich Beach. Some degradation of the East Sandwich Beach dune system did occur as a result of the storm; however, it was significantly less than that observed at Spring Hill Beach. The most severe damage to residences was observed along a 1500 foot stretch of shoreline approximately centered at the intersection of Beach Road and North Shore Boulevard. In this section, the beach was very narrow and flat, and there was little or no evidence of pre-storm dunes. Photo 25 shows a comparison of two types of building techniques. The houses on piles sustained little damage compared with the houses constructed with foundations at grade. Some dune erosion with little apparent structural damage was seen along the northernmost 2200 feet of East Sandwich Beach. Shore protection measures in this area were varied and ranged from a large stone revetment to wooden fences. The southern portion of East Sandwich Beach has accumulated significant quantities of sand, possibly transported from the north during the storm.

Photo 24

Sandwich, Massachusetts
Building on top of dunes suffered extensive damage.

Photo 25

Damage to homes on pilings
compared to homes on
at-grade foundations.

Additional Remarks. The coastline along Spring Hill Beach and East Sandwich Beach is partially sheltered by the outer arm of Cape Cod from direct wave attack from northeast storm events.

The following is a summary of FEMA's Damage Survey Report for this town:

The sand dunes along the Town Beach/Springhill Beach area was breached by wind and high water, damaging the boardwalk. Floodwaters washed out two ramps leading from the boardwalk to the beach and the parking lot at Town Beach. A footbridge and boardwalk at Boardwalk Road and Town Beach needed repairs and high winds or debris carried by floodwater damaged a chain link fence and gate on Salt Marsh Road.

The Town of Chatham is located on Cape Cod about 16 miles east of Hyannis Harbor. This site was visited by the CERC emergency assessment team on November 22, 1991.

The only site visited was Lighthouse Beach in the vicinity of the parking lot which is located near the U.S. Coast Guard Station along Morris Island Road. The parking lot, which had been used by the public for access to the beach below and for a scenic overlook, was closed due to danger posed by severe erosion of the bluff. This bluff, approximately 475 feet in length, was heavily vegetated prior to the Halloween Storm. The wooden stairway from the parking lot to the beach had been rendered unusable by loss of material which had supported its base. See Photo 26. Differences in coloration observed on the supporting posts at the base of the stairs were used to estimate the amount of material lost during the storm. The CERC emergency assessment team estimated that the base of the bluff had eroded approximately 10-15 feet at the stairway location. See Photos 27 and 28. The dark stones located at the base of the bluff are the remnants of a previously buried revetment. Sections of the asphalt parking lot which collapsed onto the face of the bluff indicated that as much as 20 feet of the bluff had been lost. Nearly all of the soil eroded from the bluff had been removed from the area by waves and currents. An armor stone revetment has since been constructed on this site to stabilize and protect the bluff.

The following is a summary of FEMA's Damage Survey Report for the Town of Chatham:

Various town streets, beaches and other public property was inundated with debris carried by the floodwaters of the Halloween Storm. Sand and other sediments were deposited on Andrew Harding Lane, other roads, parks, and buildings.

The channel at the Chatham Fish Pier required dredging due to shoaling of the channel. Navigation aids needed to be replaced or repaired in various open channels in Chatham. A drainage pipe on Chatham Harbor Beach between Andrew Harding Land and Holway Street was destroyed by the storm and required replacement. Photo 29 shows a house removed from its foundation on Holway Street. The Stage Harbor Pump Station was also damaged in the storm. Wave overtopping of revetments also scoured and eroded bluffs. See Photo 30.

Floodwaters also washed out the road surface on Holway Street, requiring the replacement of lost fill, aggregate material, and grading and shaping of the shoulders and ditches.

The parking area at Cowyard Landing was damaged during the storm, along with the boat ramp at the same location. At the Scatteree Road and Claflin Landings, the pavement of the parking lots was washed out, and a precast wall was destroyed at the Scatteree Road Landing. The chain link

Photo 26

Chatham, Massachusetts
Staircase erosion at Lighthouse Beach.

Photo 27

Loss of parking overlook at Lighthouse Beach.

Photo 28

Remains of old revetment and pavement.

Photo 29

House removed from its foundation at Holway Street.

Photo 30

Wave action and overtopping has
scoured soil above revetment.

fence at the Chatham Fish Pier was washed away and the loading dock was damaged. Gangways were also destroyed at both the Fish Pier and at the Ryder's Cove Landing. The Jacknife Harbor Landing required regrading and portions of the entrance road and parking area of Crows Pond Landing were washed out.

Erosion of the outer Cape can vary widely depending on the location of specific interest. At Race Point there was considerable erosion even though it is historically an accreting area. An off-road vehicle access route was relocated due to the erosion. From Race Point south to the High Head area there was no reported significant erosion. At Head of the Meadow Beach, portions of the parking area experienced severe erosion. See Photo 31. Photo 32 shows the loss of backfill material behind an abutment and wingwall of a bridge in Eastham. Ballston Beach in Truro experienced a dune blowout. Waves broke through the dune system and created a 90 foot wide gap. Sand washed over and through the break to the backshore area. See Photo 33. Highland Light was visited by NED personnel and it was reported that approximately 10 feet of bluff recession occurred.

Staircases leading to the beaches were lost at Marconi Beach, Nauset Light, and Coast Guard Beach. Approximately 10 feet of bank eroded at Marconi Beach, 10 to 15 feet at Nauset Light, and up to 30 feet along the Coast Guard Beach area. A foot bridge was also severely damaged at Coast Guard Beach and backfill material at a bridge abutment was lost on Doane Road in this same area. A town road north of Nauset Light was eroded and closed to traffic. The parking lot and overlook area at Lighthouse Beach in Chatham was also severely damaged due to bank recession and beach erosion. This is detailed in the section on damages about the Town of Chatham.

Photo 31

Truro, Massachusetts
Head of The Meadow Beach, damage to parking area.

Photo 32

Eastham, Massachusetts
Erosion of bridge abutment and wingwall.

Photo 33

Truro, Massachusetts
Ballston Beach dune blowout.

TOWN OF NANTUCKET

Nantucket Island is located approximately 30 miles south of Cape Cod, Massachusetts. The following observations were provided by information contained in FEMA's Damage Survey Report, NED high water mark surveys accomplished between November 5-7, 1991, and the author's personal observations made November 2, 1991.

Flood debris was deposited on various roadways and a pumping station was damaged by flood waters. A section of roadway and a boat ramp were eroded by storm waves along Harborview Way and Walsh Street. Pavement along Polpis Road was also washed out. Storm waves caused extensive damage to the town pier in Nantucket Harbor, sewer lines were clogged with debris, and the Dionis Beach House septic system was damaged.

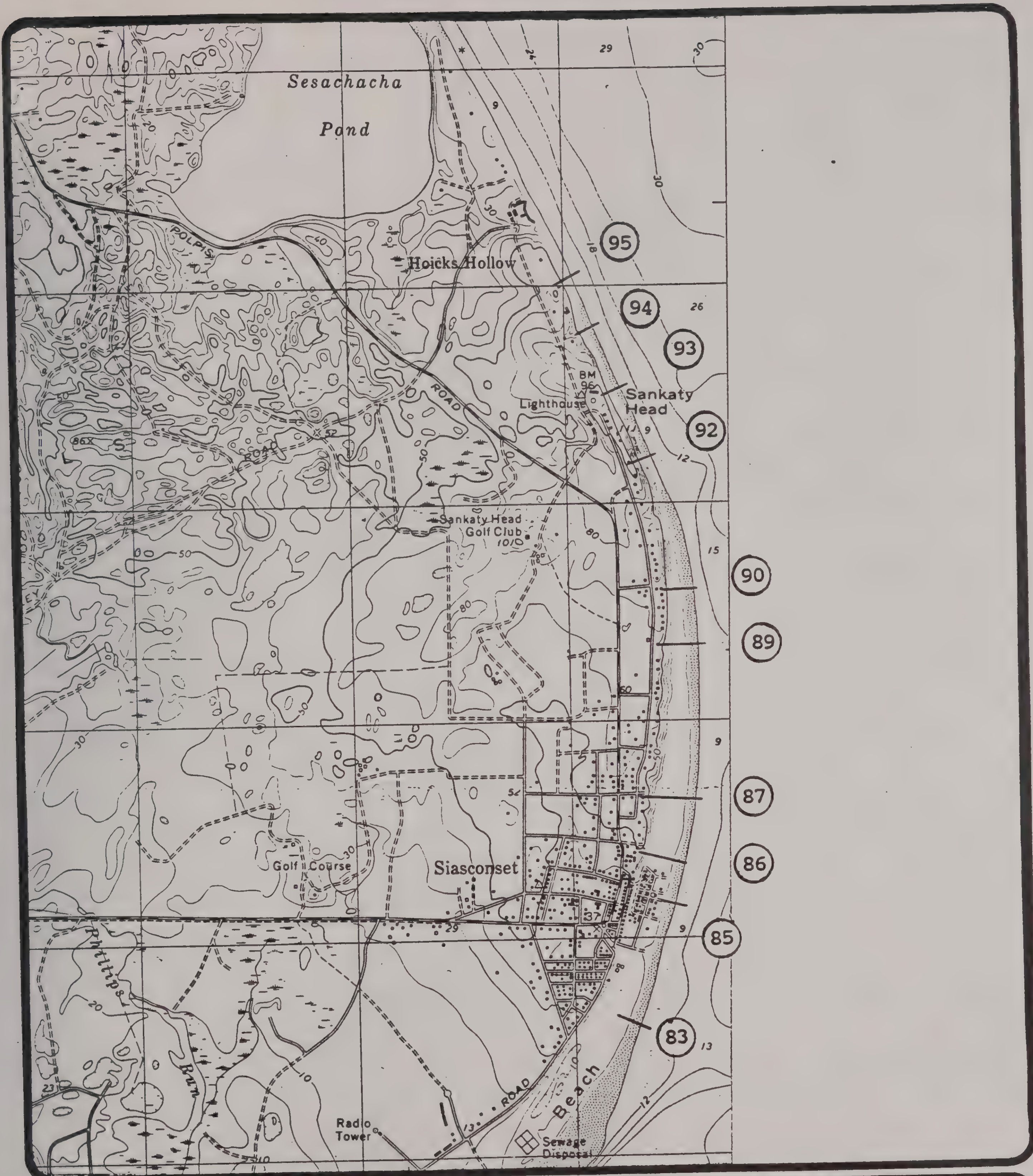
According to observations made by NED personnel, the heaviest property damage occurred in downtown Nantucket, Wauwinet, and Madaket. It was also reported that between Third and Coatue Points facing Nantucket Sound, sand dunes originally 10 to 15 feet high eroded to about 3 feet high. Four buildings at the end of North Wharf were completely destroyed along with the last 250 feet of wharf. In addition, almost all of the bulkheads protecting private homes along Nantucket Sound were damaged or destroyed. Interviews with residents and local officials revealed that this storm was more severe than the Blizzard of 1978.

The Halloween Storm also caused extensive erosion and bluff recession along the east facing shoreline of Nantucket. Several structures were endangered by unstable slopes and exposed foundations. Many of these structures have since been removed or completely destroyed by a subsequent northeaster in December 1992. Beach erosion and bluff recession measurements were made along the east shore immediately following the storm by Dr. Franklin W. Fessenden as part of an independent study of the area. This area includes Siasconset, Codfish Park and Sankaty and was monitored September 29, 1991 and then again on November 2, 1991. Since the original measurements took place after Hurricane Bob, there were no other influencing factors due to other storms. The location of the measurements are shown in Figure E-1. Table 1 summarizes the bluff recession and beach erosion that occurred at Dr. Fessenden's transect stations.

TABLE 1

TRANSECT	DESCRIPTION
95	Bluff recession = 14.5'
94	Bluff recession = 12.0'
93	Bluff recession = 8.5'
92	Bluff recession = 10.2'
90	Beach erosion = 44' (+/- 5')
89	Beach erosion = 20.9'
87	Beach erosion = 30.2'
86	Beach erosion = 26.1'
85	Beach erosion = btwn. 41' and 50'
83	Beach erosion = 23.5'

Photo 34 shows the condition of the bluff at Transect 95. There was a dramatic recession of the bluff face which ultimately resulted in the abandoning and subsequent removal of this house. Photo 35 shows the area in the vicinity of the Sankaty Head Lighthouse (Transect 93). Loss of bluff material and steepening of face led to the destruction of a chain link fence. Also note the proximity of the house to the edge of bluff. Photo 36 at Transect 89 shows a portion of the lower beach. The edge of the dune is denoted by the vegetation and scarp. This dune was eroded approximately 20 feet back from the ocean. Photo 37 at Transect 85 shows the results of dune erosion and subsequent damage to houses. The loss and recession of the dune was extreme in this area. At Transect 85, the dune line receded between 41 and 50 feet, threatening the foundations and structural integrity of numerous houses. These photographs dramatically illustrate the destructive power of the Halloween Storm of 1991.



Halloween Coastal Storm Evaluation

Figure E-1

7.5 Minute Quadrangle - Siasconset, Mass.

New England Division

U.S. Army Corps of Engineers

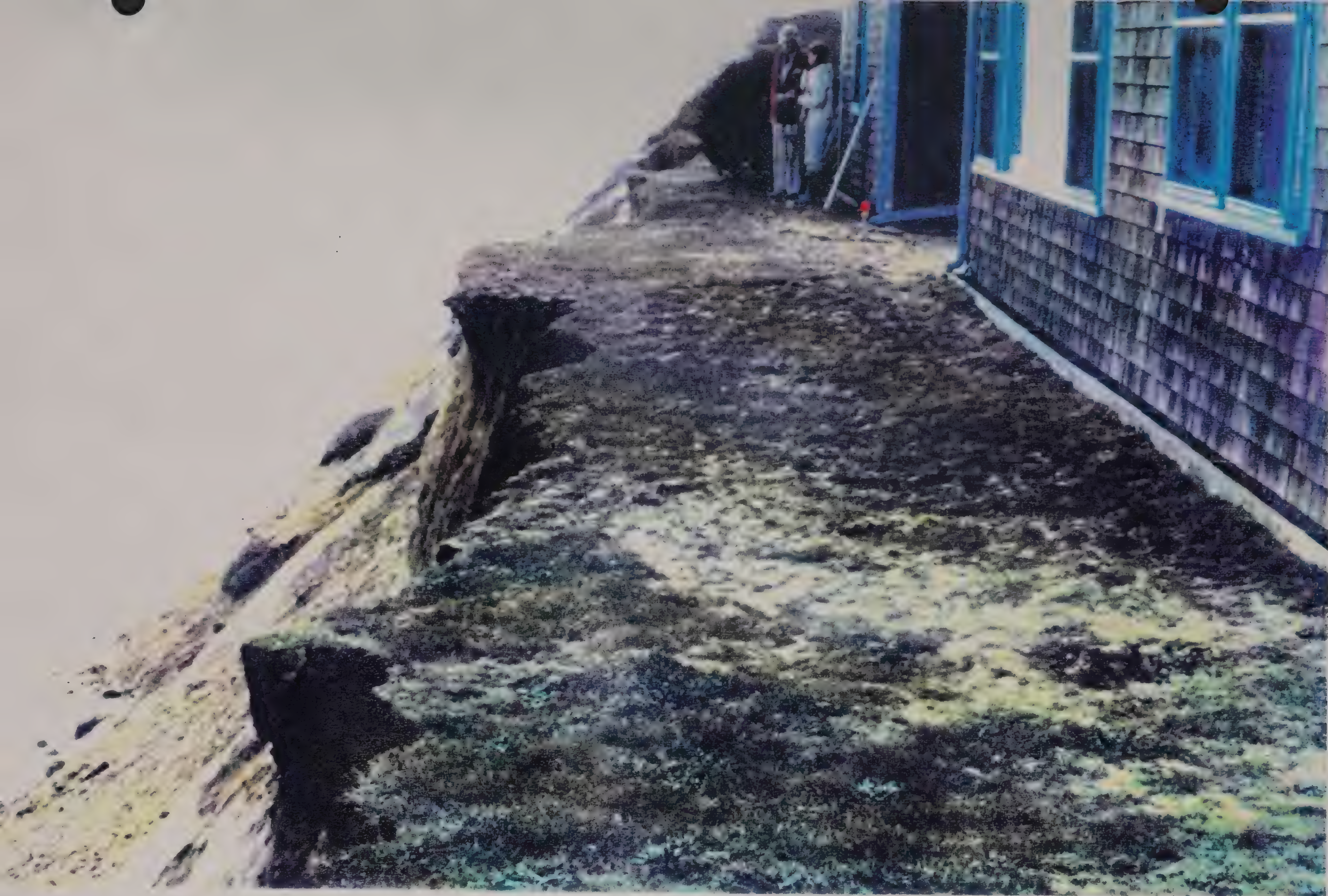


Photo 34

Siasconset, Massachusetts
Bluff recession endangering house which
has since been removed (Transect 95).

Photo 35

Sankaty Head Lighthouse,
Nantucket, Massachusetts
Loss of fence and steepening
of bluff. (Transect 93)

Photo 36

Siasconset, Massachusetts
Dune scarp eroded approximately 20'.
(Transect 89)

Photo 37

Siasconset, Massachusetts
Dune erosion (40-50') threatens houses. (Transect 85)
These houses were subsequently destroyed during
the northeaster of December 1992.